UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Memorandum

Date: August 16, 2010

TO : Jay Howell, Assistant Executive Director,
Office of Hazard Identification and Reduction (EXHR)

THROUGH: Mary Ann Danello, Ph.D., Associate Executive Director,
Directorate for Health Sciences
Lori E. Saltzman, M.S., Director, Division of Health Sciences

FROM : Treye A. Thomas, Ph.D., Toxicologist, Office of Hazard Identification and Reduction (EXHR)

SUBJECT : CPSC Staff Review of Ozone-generating Air Cleaners*

Introduction

In Fall 2004, the U.S. Consumer Product Safety Commission (CPSC) contracted with Richard Shaughnessy, Ph.D., an internationally recognized expert on indoor air quality issues. Dr. Shaughnessy was tasked with evaluating the adequacy of an existing U.S. Food and Drug Administration (FDA) maximum acceptable level of 0.05 parts per million (ppm) for ozone released from indoor air cleaning devices (IACDs), and specifically ozone generating air cleaners (OGAC). His evaluation ("contractor report") was subsequently reviewed by outside peer reviewers who provided comments and recommendations to the CPSC staff. The CPSC staff completed a report that reviewed the results of the contractor report and the peer review comments. The contractor report and CSPC staff report were posted on the CPSC website in October 2006 for a 45-day comment period. Several comments were submitted and a summary of these comments and staff responses can be found in Appendix A of this memorandum. CPSC staff memos addressing the technically complex issues surrounding the use of OGACs can be found in Appendices B through D.

The purpose of this memorandum is to provide background information on OGACs and potential health effects related to the use of certain OGACs, to summarize the findings of the CPSC staff, to address the peer reviewer comments, and to provide the staff's conclusions and recommendations for next steps.

* This memo and accompanying reports were prepared by the CPSC staff; they have not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.

Background

Ozone is a reactive gas consisting of three oxygen atoms that is formed in the atmosphere through a series of photochemical reactions. Ozone may also be produced by electrical discharges, such as lightning and certain high voltage electrical devices. Exposure to ozone predominantly affects the respiratory system, causing adverse health effects such as throat irritation, pulmonary edema, and reduced lung function, with symptoms such as cough and shortness of breath.

Increasing awareness by the public regarding exposures to chemicals and the potential adverse health effects of indoor air pollutants may contribute to the popularity of air cleaners. Many consumers purchase air cleaners under the belief that these devices can remove from the air a variety of chemicals, dust, and pollen that some consumers associate with health problems. A significant number of those individuals who purchase air cleaners do so because of health concerns, such as asthma or allergies (Peternel 2008; Sedney 2008). Available data suggest that annual sales of air cleaners in the United States range from $410 million to $500 million (Peternel 2008).

Several types of portable air cleaners may be used in the home. One type uses filtering systems, such as high efficiency particulate air (HEPA) filters, to remove pollutants. Electrostatic precipitators use electrically charged metal plates to attract and trap pollutants. Ionizers release charged particles into the air that cause particulate pollutants to agglomerate and precipitate out of the air. Finally, ozone generators are devices that intentionally produce ozone, which purportedly controls indoor air pollution. Some products combine more than one technology type into a single hybrid product. While all types of air cleaners potentially produce some ozone as a by-product of their normal operation, ozone generators may release significant quantities of ozone into the indoor air.

In 1976, the FDA published regulations for medical devices that generate ozone by design or as an inadvertent or incidental by-product. FDA established 0.05 parts per million (ppm) (or 50 ppb) as the maximum acceptable level of ozone "in the atmosphere of enclosed space intended to be occupied by people for extended periods of time, *e.g.*, houses, apartments, hospitals, and offices" (21 C.F.R. § 801.415)[*]. Although firms may imply certain health benefits of their products, and consumers may believe that they derive health benefits from the use of air cleaners, the FDA does not consider air cleaners to be medical devices.

While the U.S. Environmental Protection Agency (EPA) does not have jurisdiction over air cleaner devices, it regulates outdoor levels of ozone under the Clean Air Act through National Ambient Air Quality Standards (40 C.F.R. § 50.9; 40 C.F.R. § 50.10). Recently, the EPA reduced the standard for outdoor ozone from 80 ppb to 75 ppb for eight hours. The State of California Air Resources Board (CARB) sets standards for outdoor levels of ozone in California, which currently are 90 ppb for one hour, and 70 ppb for eight hours (Title 17, California Code of Regulations, Section 70200). California will begin regulating all indoor air cleaning devices,

[*] A standard such as the FDA's 50 ppb maximum acceptable level should be considered an "accumulation level" and not an "exposure limit." In scientific terminology, an exposure limit incorporates a time factor. For example, the National Ambient Air Quality Standards, established by the U.S. Environmental Protection Agency (EPA), currently set the exposure limit for outdoor ozone at 75 ppb for eight hours.

both medical and non-medical, under California Assembly Bill 2276 (Pavely Bill). That bill adopts the federal ozone emissions limit for air cleaning devices established by the FDA of 50 ppb.

IACDs are consumer products under the jurisdiction of CPSC, although CPSC has not promulgated any specific rule concerning the release of ozone from air cleaners. In the public comments submitted to CPSC staff, consumer advocacy groups, state health departments, and other entities requested that CPSC set indoor ozone limits for all air cleaners.

Voluntary Standards and State Regulations

Underwriters Laboratories (UL) and the State of California have taken significant action to address the potential health effects of ozone released from air cleaners. Underwriters Laboratories formed a working group to revise its *Standard for Electrostatic Air Cleaners* (UL 867 Section 37). A revised testing method was approved in December 2007. The UL working group developed clarifications for the ozone test procedures of electrostatic air cleaners, ionizers, and ozone generators, which were included in the revision. UL 867 does not apply to mechanical air cleaners that use only filters (e.g., HEPA) to clean the air (UL 2008, Appendix E). Factors considered by the working group included chamber size, direction of air cleaner exhaust, air exchange rates, and length of testing. UL 867 outlines specific testing procedures to determine the amount of ozone that an air cleaner produces. The UL standard incorporates the FDA limit of 50 parts per billion (ppb) for ozone produced by air cleaning devices. The UL standard is expected to be adopted by the American National Standard Institute (ANSI). The revised standard is commonly referred to as the ANSI/UL Standard 867 test method or simply the 867 test method.

In September 2006, California Assembly Bill 2276 (2006, Pavley) was signed, directing the California Air Resource Board (CARB) to develop and adopt a regulation to limit the ozone emitted from indoor air cleaning devices in order to protect public health. The bill required the CARB to adopt the September 21, 2007 version of Section 37 of the ANSI/UL Standard 867 test method. The bill requires manufacturers of air cleaners to have their devices tested by independent laboratories using the UL 867 guidelines and receive a certification from the State of California that verifies their compliance with the new regulation. The regulation became effective October 18, 2008.

CPSC Staff Reports

The CPSC staff formed an ozone team comprised of staff from various technical directorates within the agency and reports were written by staff from the Directorate for Health Science (HS), the Directorate for Economic Analysis (EC), and the Directorate for Engineering Sciences, Division of Human Factors (HF). The team members' reports (memos) address the issues raised in the public comments. These reports include a review of the socio-demographic profile of households that purchase air cleaners, the use patterns, and the potential exposures to ozone from these devices.

The report from EC staff provides an overview of the market for air cleaners (Peternel 2008, Appendix B). The analysis of existing data suggests that there are several million people in the United States who live in a household where an OGAC is present. (Peternel 2008, Appendix B). Households that own air cleaners typically report a higher than average annual household income, and most households that own an air cleaner are composed of two adults. Approximately one-third (37%) of all households that own an OGAC have at least one child.

CPSC HF staff completed a report that describes the likely use of IACD's by consumers (Sedney 2008, Appendix C). The HF report found that the most common residential use of IACD entails one device operating continuously in a bedroom. This appears to be a logical basis for selection of "worst case" scenarios because bedrooms typically are smaller than common-use areas of the home, and are more likely to be enclosed (i.e., with the door fully or partly closed, thereby potentially limiting airflow). HF staff's assessment assumes that ozone emissions in a bedroom would have limited impact on other areas of the typical residence, a single family home. By extension, HF staff defines the "reasonable worst case among healthy individuals" based on the subgroup that spends the highest proportion of time in a bedroom. On average, children aged one to four years spend 12.37 hours per day in a bedroom, more than any group, and may represent a "reasonable" worst-case timeframe for the "typical" use scenario (Sedney 2008; Table 2, Appendix C). The 95th percentile exposure in that subgroup, again for the most common use scenario, is 16.50 hours per day. For households using multiple devices, suggesting a higher and perhaps more consistent exposure throughout the time indoors in a residence, the daily average time spent in the house is 20.19 hours for a child aged one through four, and 19.58 hours for the average adult over age 64.

The HS report focuses on estimating actual consumer exposures to ozone resulting from the use of devices that meet the revised UL 867 standard (Babich 2008, Appendix D). Mass balance models (NRC 1981) were used to estimate indoor ozone levels in residences. One-zone, two-zone, and multiple-zone models were used. Steady state conditions were assumed, because air cleaners may be operated for several hours or continuously (Piazza et al. 2007; Sedney 2008). The one-zone model was used to model a bedroom, which represents a typical use scenario (see Figure 1, Babich 2008) (Piazza et al. 2007; Sedney 2008). With the two-zone model, zone one was a bedroom containing the ozone source and zone two was the rest of the house. Some consumers may use multiple air cleaners in different rooms (Piazza et al. 2007; Sedney 2008). Thus, the multiple-zone model was used to model a scenario in which three ozone sources were operating simultaneously in three bedrooms. Other zones included a hallway and the rest of the house.

Based on the modeling of ozone emissions from air cleaners, the HS report concludes that UL 867 is adequate to maintain ozone levels below 50 ppb in residences under reasonably foreseeable use conditions. Assuming the operation of one UL 867-compliant air cleaner in a bedroom with the door closed, it is estimated that the steady-state ozone level will be below 50 ppb in greater than 99.9% of cases. The HS analysis encompasses variability in homes, including: room size, infiltration rate, total house size, reactive decay rate, and ambient (outdoor) ozone levels (Babich 2008). The HS analysis also considers regional and seasonal variation, and the simultaneous operation of multiple air cleaners in different rooms. Limited experimental data (Jakober and Phillips 2008) are consistent with the modeling studies presented here.

UL 867 specifies that ozone measurements should be made near the outlet of the device, where ozone concentrations are highest, rather than elsewhere in the test chamber, which is the standard practice for measuring source strengths. This procedure is intended to protect consumers who may place the air cleaner near their breathing zone (which is not recommended). However, based on the analysis in the HS report, the UL procedure overestimates the ozone source strength by 2-to-3-fold. Therefore, the UL testing procedure likely overestimates the average indoor ozone levels, that is, the levels a few feet away from the source. This, in effect, provides an additional safety factor of 2-to-3-fold for consumers who correctly position UL 867 compliant air cleaners away from their breathing zone.

Sensitive Populations

The CPSC staff's market and use analysis of air cleaners in the United States found that a large number of individuals who are exposed to air treated by ozone generating air cleaners may have a respiratory condition that might classify them as sensitive receptors (Peternel 2008, Sedney 2008). The public comments indicated that certain epidemiologic studies have suggested that ozone effects may occur at lower concentrations, particularly for sensitive populations.

The CPSC staff conducted a brief review of the epidemiologic studies that were referenced in reviewer comments as possible evidence to support a lower exposure limit. The CPSC staff considered whether the new studies provided sufficient data to meet the Commission guidelines for determining chronic toxicity, 16 C.F.R. § 1500.135, and found that the studies are insufficient due to certain inadequacies of the study design and potential confounders for exposure classification. Under CPSC regulations, adverse health effects observed in both animal and human studies must be considered "sufficient" to justify proceeding with setting an exposure limit. For example, clinically significant decreased lung function may be considered a "substantial" health effect, but reversible irritation of the respiratory tract may not be sufficient to justify setting an exposure limit.

While there is evidence in the peer-reviewed literature of significant adverse health effects of ozone at concentrations below 50 ppb for the general and sensitive populations, and one peer reviewer thought that there was no threshold exposure limit below which there were no health effects for sensitive populations, it appears that the current studies do not provide sufficient data to determine a specific or separate standard for sensitive populations.

Conclusions and Recommendations

The CPSC staff concludes that the contractor report results are reasonable and that, based on available data, the 50 ppb ozone limit is sufficient to protect the general population during reasonably foreseeable use conditions. The CPSC staff reviewed new studies that suggest lower exposure levels may be needed for sensitive populations; however, the existing data do not appear to be sufficient, based on CPSC guidelines, to specify a separate level for sensitive populations. If these devices are kept at a distance of several feet away from the individual, the actual ozone exposure from the device may be 2-to-3-fold lower than 50 ppb for devices that meet the updated UL 867 standard (Babich 2008). Additionally, there are a number of air cleaners on the market that do not produce ozone (e.g., HEPA filters) and are comparable to ozone generating air cleaning devices in terms of price, availability, and efficiency in cleaning the indoor air.

Based on the contractor report and input from scientists with expertise in ozone health standards, CPSC staff believes that the UL 867 standard sets the appropriate limit for ozone production for portable air cleaners. Staff will continue to monitor the implementation of the UL 867 standard and its application in the California regulations. The State of California began regulating portable air cleaners on October 18, 2008. Accordingly, CPSC staff recommends that the regulatory approaches adopted by the State of California be observed to determine whether the updated UL testing procedures are adequate to address health effects of ozone levels resulting from OGAC use in households. During this period, CPSC staff recommends that manufacturers of air cleaning devices comply with the updated UL 867 standard.

Modeling by CPSC staff and studies by the California EPA suggest that in typical exposure scenarios, the farther away an individual is from an OGAC, the lower the concentration of ozone (Babich 2008). Thus, CPSC staff believes that users of an OGAC should maintain a maximum distance away from these devices, and devices should be placed in a location in a room farthest away from the room occupants. Sensitive groups might also consider limiting the time they spend in air that is treated by these devices.

Sensitive individuals concerned about the development or exacerbation of existing health conditions that may result from ozone exposure should consider purchasing devices that do not produce ozone. Such cleaners typically use a filtering media (e.g., HEPA) to remove pollutants from the indoor air, and are comparable to ozone-generating devices in price, availability and performance. EPA staff, along with CPSC staff, has produced a guidance document on selecting an air cleaner (EPA 1990; 2007). Non-governmental organizations (NGOs) have also produced reviews of air cleaners and provide guidance on selecting a suitable device (e.g., American Lung Association).

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Appendix A

UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Memorandum

Date: December 4, 2008

TO : Mary Ann Danello, Ph.D., Associate Executive Director, Directorate for Health Sciences

THROUGH : Lori E. Saltzman, M.S., Director, Division of Health Sciences

FROM : Treye A. Thomas, Ph.D., Toxicologist, Division of Health Sciences

SUBJECT : Response to Public Comments on Ozone-generating Air Cleaner Project Staff and Contractor Reports*

Introduction

This memorandum provides the Directorate for Health Sciences (HS) staff responses to comments made to the U.S. Consumer Product Safety Commission (CPSC) staff on a contractor report and the subsequent CPSC staff report on ozone-generating air cleaners (OGACs). In Fall 2004, CPSC contracted with Richard Shaughnessy, Ph.D., an internationally recognized expert on indoor air quality issues to complete a report on the adequacy of an existing U.S. Food and Drug Administration (FDA) maximum acceptable level of 0.05 parts per million (ppm) for ozone released from indoor air cleaning devices (IACDs). The contractor report was subsequently reviewed by outside peer reviewers to provide comments and recommendations to the CPSC staff. The CPSC staff completed a report that reviewed the results of the contractor report and the peer review comments. The contractor report and CSPC staff report were posted on the CPSC website in October 2006 for a 45-day comment period. Several comments were submitted by a number of individuals and organizations and a summary of these comments and staff responses can be found in this memorandum.

Comment:

One or more commenters stated that many consumers who purchase air cleaners are looking for relief from asthma or allergies, are more sensitive to the effects of ozone, and may experience health effects at concentrations below 50 ppb. Commenters also suggested that a lower limit for the general population should also be considered because some studies suggest that health effects from ozone may occur at lower concentrations (e.g., 20-30 ppb).

* This memo and accompanying reports were prepared by the CPSC staff; they have not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.

Response:

CPSC staff conducted a review of available data to estimate the population of sensitive individuals who may be exposed to ozone-generating air cleaners. Although the data are limited, there is evidence to suggest that a large number of consumers who purchase indoor air cleaning devices (IACDs) do so because they or a family member have an existing health condition such as asthma (Peternel 2008, Sedney 2008). The CPSC staff has reviewed studies that were not included in the Shaughnessy report that suggest lower ozone exposure levels may be appropriate for sensitive populations. Staff believes the data are not sufficient to identify a level that is specific for sensitive populations or to support lowering the current 50 ppb limit for the general population.

CPSC staff suggests that sensitive populations exercise caution when using IACDs that produce ozone both intentionally and unintentionally. Ozone-producing IACDs, unlike fans, should be placed several feet away from a sensitive individual; available data and modeling by CPSC staff suggest that ozone exposure levels decrease significantly the farther away the device is from the individual (Babich 2008).

There are several air cleaners available that do not produce ozone, and are comparable in price, efficacy and availability to devices that do produce ozone. The U.S. EPA along with the CPSC staff, and consumer and advocacy groups have produced guidance documents on selecting an appropriate IACD, including those that do not produce significant quantities of ozone (EPA 1990; 2007). Consumers who are concerned about exposure to ozone from IACDs should consult these publications to identify the IACD that best suits their individual needs.

Comment:

Several comments suggested that fifty (50) ppb may not be adequate for long-term exposures that may occur in some consumer use scenarios.

Response:

The contractor report concluded that the 50 ppb level is sufficient to protect the general U.S. population during normal use of an air cleaner. Significant health effects in humans at concentrations below 50 ppb have not been well established in the peer-reviewed literature. The 50 ppb level is expected to be protective for time periods that may be experienced in consumer use scenarios for air cleaners. The CPSC staff has reviewed a number of recent studies on the effects of low-level ozone exposures to humans. However, at this time, the available data are not sufficient to support a lower limit when reviewed under CPSC guidelines for determining chronic toxicity.

The CPSC staff reports suggested that devices that meet the updated UL 867 standard may produce exposures to ozone that are significantly below 50 ppb if the device is placed several feet away from the consumer (Babich 2008). Thus, actual consumer exposures may be considerably lower than 50 ppb for those consumers that use devices that meet the new UL standard.

If consumers are concerned about exposure to ozone or experience any adverse health effects they believe are related to ozone, they are encouraged to consider purchasing a device that does not produce ozone. There are several types of air cleaners that are comparable to ozone-generators in price and efficacy. Consumers can consult guidance documents produced by the EPA and CPSC, as well as those of other organizations, for advice on selecting a suitable air cleaner.

Comment:

One comment suggested that manufacturers of air cleaners should place warning labels on their products to indicate that ozone is produced and may cause health effects in asthmatics.

Response:

Warning labels, if used, should advise consumers that these devices do produce ozone and there may be acute effects such as lung irritation from misuse. These devices are not fans and should not be used in close proximity to the breathing zone. For example, in a bedroom, an ozone-emitting air cleaner should be placed in the portion of the room that is farthest away from the bed. CPSC staff has conducted modeling studies that are supported by monitoring studies that demonstrate that the farther away a person is from these devices, the lower the concentration of ozone will be. CPSC staff also recommends that consumers should limit or discontinue their use of ozone-generating air cleaners should they experience any adverse health effects.

Comment:

Several comments stated that the CPSC staff should perform additional modeling studies to include more conservative assumptions, such as lower air exchange rates, lower decay, higher ambient ozone levels, background levels, and the use of multiple air cleaners. CPSC staff should also consider the ranges of air exchange rates, decay rates, and ambient ozone levels encountered in the real world. Most importantly, CPSC staff should consider the infiltration of ambient ozone on indoor ozone levels.

Response:

The CPSC staff performed additional modeling studies to assess the distribution of indoor ozone levels resulting from the use of ozone-generating air cleaners in residences (Babich 2008). These studies used both deterministic and probabilistic approaches. The studies also included empirical distributions for air infiltration rate, ozone decay, surface area-to-volume ratio, room size, house size, and ambient ozone concentration. These studies employed one-zone, two-zone, and multiple-zone models. The use of multiple air cleaners in different rooms was also considered.

Based on these modeling studies, the CPSC staff concluded that UL 867 is adequate to maintain ozone levels below 50 ppb in residences under reasonably foreseeable conditions. Assuming the operation of a UL 867-compliant air cleaner in a bedroom with the door closed, staff estimates that the steady-state ozone level will be below 50 ppb in greater than 99% of cases (Babich 2008).

Comment:

One commenter suggested that setting a limit on the emission rate is an appropriate approach to limiting ozone exposure from air cleaners.

Response:

The CPSC staff agrees that an emission rate limit may be an appropriate, even preferred, means of limiting ozone exposure. However, UL 867 is based on a concentration limit, that is, a maximum of 50 ppb in the test chamber. The UL test method is probably more practical for routine certification and compliance testing. In addition, the 50 ppb limit roughly equates to an emission rate (or source strength) of 2 cc/h (4 mg/h). Therefore, the UL approach is also appropriate for limiting ozone emission from air cleaners.

Comment:

One commenter noted that ozone measurement should be made two inches from the discharge point of the device.

Response:

UL 867 requires ozone measurements to be made near the discharge point of the device. The CPSC staff recommends that consumers should place these devices several feet away; available data and modeling by CPSC staff suggest that ozone exposure levels decrease significantly the farther away the device is from the individual using it (Babich 2008). This provides an additional margin of safety provided that the air cleaner is not positioned directly in front of an individual's face.

Comment:

One commenter suggested that the CPSC staff consider effects of age, dust, and fine particulate matter (high PM_{10} levels) on the ozone emission rate. These factors may increase ozone emission rates by 2-fold.

Response:

The CPSC staff did not perform laboratory or field studies to assess the effects of age or environmental conditions on the ozone emission rate. However, UL 867 requires ozone measurements to be made near the discharge point of the air cleaner. Modeling indicates that ozone levels farther away from this point are typically 2-to-3- fold lower. This provides an additional margin of safety, provided that the air cleaner is not positioned directly in front of the user's face. Therefore, even with a 2-fold increase in ozone emissions over the lifetime of the product, ozone levels are not expected to exceed 50 ppb. Furthermore, transient increases in dust or PM_{10} levels, for example, should result only in a transient increase in ozone levels.

Comment:

One commenter questioned the assumption of steady-state conditions in the modeling described by Dr. Shaughnessy (2006). The commenter stated, "There are surely cases where ozone never reaches a steady state but accumulates until the air cleaner is turned off."

Response:

Dr. Shaughnessy and the CPSC staff both assumed steady-state conditions in the modeling of ozone levels in residences. When an air cleaner is switched on, ozone levels accumulate until steady state conditions are attained. Steady state is, by definition, the point at which the ozone concentration reaches its maximum level. It may take a few hours before steady state is reached. The steady state assumption was applied, because consumers may operate air cleaners for long periods of time, or even continuously. The assumption of steady state conditions may overestimate the ozone exposure in cases where the air cleaner is used for short time periods, thus providing an additional margin of safety for these use patterns.

Comment:

One commenter questioned the propriety of basing public policy decisions on mathematical models. The commenter cited examples of models that failed due to unrealistic assumptions, oversimplifications, and data gaps.

Response:

The CPSC staff is aware of both the utility and limitations of mathematical models in assessing human health risks. In assessing exposure to pollutants such as ozone, direct measures of exposure, such as from field studies, are always preferred (CPSC 1992). Unfortunately, such data are not always available, as they are more difficult and expensive to obtain. Mathematical models, in combination with empirical data from laboratory or field studies, such as those performed by Dr. Shaughnessy and the CPSC staff, are an appropriate alternative, provided that the limitations are understood.

In the present case, the mass-balance models used to estimate indoor ozone levels are generally well accepted and widely used (NRC 1981). The models have been validated against empirical data for various pollutants. The input parameters used by Dr. Shaugnessy and the CPSC staff are based on empirical data obtained in actual residences, and the consumer use patterns are based on consumer surveys. Limited data from a test room (Jakober and Phillips 2008) tend to support the conclusions of the CPSC staff modeling study.

Comment:

One commenter stated that Dr. Shaughnessy's conclusion that a maximum emission rate of 14 to 26 mg/h may not be adequate to maintain ozone levels below 50 ppb.

Response:

Dr. Shaughnessy (2006) estimated that the maximum source strength in a residence would be from 14 to 26 mg/h. Shaughnessy used a one-zone model with a range of room sizes from 15 m^3 to 40 m^3. He also assumed an air infiltration rate of 0.35 h^{-1}, deposition velocity of 1.76 m/h, and an ambient ozone level of zero.

The CPSC staff estimated a maximum source strength of 10 to 26 mg/h under average conditions, that is, average room size, infiltration rate, average decay rate, and average ambient ozone level. This is consistent with the conclusions of Dr. Shaughnessy.

Comment:

Several commenters noted that CPSC should consider the formation of secondary reaction products (reaction products of ozone with other pollutants). Secondary products may be more hazardous than ozone itself.

Response:

A growing body of research has reported that ozone reacts with other indoor pollutants such as volatile organic compounds (VOCs) (for example, Sarwar and Corsi 2007; Weschler 2000; Weschler et al. 1992). The sources of the VOCs may include, but are not limited to, cleaning and fragrance products. The reaction of ozone with VOCs may lead to the formation of products such as aldehydes and fine particles that may themselves present a health problem to consumers. However, there are many potential sources of VOCs, and the processes leading to the formation of secondary products are complex. Consideration of secondary products is beyond the scope of the work performed by Dr. Shaughnessy and the CPSC staff.

Two factors may tend to reduce the formation of secondary products. First, reducing ozone emissions from air cleaners should logically also reduce the formation of secondary reaction products. Second, individuals with allergies or asthma who are sensitive to odors or fragrances may be likely to limit their use of fragrance products or other products that release VOCs.

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Appendix B

UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Memorandum

Date: December 3, 2008

TO : Treye Thomas, Ph.D., Team Leader, Division of Health Sciences

THROUGH : Gregory B. Rodgers, Ph.D., Associate Executive Director, Directorate for Economic Analysis
Deborah V. Aiken, Ph.D., Senior Staff Coordinator, Directorate for Economic Analysis

FROM : John W. Peternel, Economist, Directorate for Economic Analysis

SUBJECT: Ozone generating air cleaner device market analysis*

This memo provides background information related to the use of and the market for portable ozone generating air cleaners. It proceeds as follows: the first section defines the portable air purifier market; the second section provides estimates for market data including sales, number in use, and the average product life for ozone generating portable air purifiers; the third section identifies household characteristics and use patterns for owners of ozone generating air cleaner purifiers; and the last section summarizes findings and provides guidance with regard to estimated domestic consumption and usage patterns of ozone generating air cleaner devices.

Defining the Product

The market for portable indoor air cleaning devices (IACDs) includes three types of products: intentional ozone generators, byproduct devices (including ionizers and electrostatic precipitators), and mechanical filtration devices.

The IACD market may also be segmented into two broad groups based on ozone emission levels. One group of devices may emit ozone and another group of devices that emits de minimis ozone levels. Any device that emits ozone is considered to be an ozone generating air cleaner device (OGAC). The OGAC market includes both intentional ozone generators and byproduct devices; mechanical filtration devices in contrast, emit de minimis levels of ozone and are therefore not considered OGAC devices.

Within the OGAC market, the level of ozone that an individual device emits varies widely. Intentional ozone generators have the potential to emit ozone in levels higher than specified in

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the UL 867 Standard. [*,†] Byproduct devices (BP), which unintentionally emit ozone, may be classified into two categories: 1) BP high emitters, which are believed to emit ozone in concentrations that are near or exceed the UL 867 standard; and 2) BP low emitters, which emit ozone in concentrations well below the UL 867 standard.[‡]

Market Data

a. Sales Data

Portable air cleaner devices are classified within NAICS 335211, *Electric Housewares and Household Fan Manufacturing* and comprise a very small portion of the index.[§] Therefore, no lower level NAICS data are published specifically for portable air purifiers. In general, reliable sales data for portable air cleaner devices are not readily available.[**] Some sources suggest that annual sales for portable indoor air cleaning devices range between $410 million to $500 million.[††,‡‡,§§] Another source estimates that the domestic market for portable indoor air cleaning device sales will grow by 76% from $275 in 2003 to $485 million in 2013.[***] These sales estimates include both ozone generating, either intentionally or as an unintentional byproduct, and de minimis portable air purifiers.

Prices for portable indoor air cleaning devices range from less than $100 to over $600, while the average ozone generating air cleaner costs between $200 and $500.[†††] Mechanical filtration devices typically cost less than ozone generating air cleaners with unit prices ranging from $40 to $200.[‡‡‡,§§§] In addition, results from a California survey indicate the following median prices

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[*] "Ozone Generating Air Cleaners and Indoor Chemistry", Environmental Protection Agency. January 10, 2007. http://www.epa.gov/appcdwww/iemb/ozone.htm (visited on August 6, 2008)

[†] Some intentional ozone generators have an automatic shutoff mechanism which may limit ozone emissions to 50 ppb (i.e., the UL 867 Standard). However, currently available data does not allow for estimating the number of devices with these automatic shutoff mechanisms.

[‡] Technically, hybrid devices, which use multiple air cleaning methods, is a fourth classification of portable air cleaner devices. However, for the sake of analysis hybrid devices are classified within the three stated product types.

[§] NAICS is an acronym that stands for North American Industry Classification System.

[**] REPORT: Evaluation of Ozone Emissions from Portable Indoor Air Cleaners: Electrostatic Precipitators and Ionizers. February 2008. Staff Technical Report. California Environmental Protection Agency (http://www.arb.ca.gov/research/indoor/esp_report.pdf)

[††] "New concern about ionizing air cleaners" CR Investigates. May 2005. Consumers Union

[‡‡] The Boston Globe Online. Despite doubts, air cleaners are big business" Cindy Atogi. September 16, 2007. (http://www.boston.com/business/articles/2007/09/16/despite_doubts_air_cleaners_are_big_business/)

[§§] Siegel http://www.engr.utexas.edu/news/articles/20050915903/index.cfm ($500 million)

[***] Freedonia Group, Inc., 2004 Consumer Water Purification & Air Cleaning Systems to 2008. Report No. 1829 Cleveland OH.

[†††] National Geographic Online. *The Green Guide*. "Air Purifiers: What to Look for" http://thegreenguide.com/reports/product.mhtml?id=13&sec=2 (Visited March 15, 2008)

[‡‡‡] National Geographic Online. *The Green Guide*. "Air Purifiers: What to Look for" (http://www.thegreenguide.com/products/Appliances/Air_Purifiers/2) (Visited March 15, 2008)

[§§§] New York Times. "How to Select an Air Cleaner", Jay Romand. February 11, 2007 (http://www.nytimes.com/2007/02/11/realestate/11home.html?scp=5&sq=air+purifier&st=nyt)

for portable indoor air cleaning devices: intentional ozone generators ($300), byproduct devices ($250) and mechanical filtration devices ($90).[*]

The California survey collected additional data, which are useful for constructing an estimate of unit sales for various types of portable indoor air cleaning devices.[†] The survey results provide the following information on the share of unit sales for each type of device: intentional ozone generators (18%), byproduct devices (62%) and mechanical filtration devices (20%).[‡] Another California study has estimated that 20% of the byproduct devices emit ozone near or in excess of the UL 867 standard.[§]

It is important to note that California recently passed California Assembly Bill 2276, which limits IACD emissions to 50 ppb as defined under UL Standard 867 effective October 2010.[**] This regulation may change the mix of products produced and sold in the future.

Notwithstanding, using the share data and the median price results reported above, it is possible to construct a weighted average price ($227) for indoor air cleaning devices ($300 * 18% + $250 * 62% + $90 * 20%). Dividing the estimate of $400 to $500 million annual industry revenue by the weighted average price ($227) yields an estimate for annual unit sales of approximately 1,760,000 to 2,200,000 million devices. Applying market share estimates yields the results presented in Table 1.

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[*] "Draft Economic Impact Assessment for Regulation of Ozone Emissions from Indoor Air Cleaning Devices" Research Division California Resources Board. (June 14, 2007) http://www.arb.ca.gov/research/indoor/aircleaners/2276_econ_section_6-14.pdf

[†] Note that the CA survey applied only to CA residents, and, thus, may not reflect the US domestic market as a whole. Also, the survey was based on 2,019 respondents, of which only 284 had IACDs. Thus, the small sample size may limit the survey's reliability.

[‡] For an explanation of market share estimates see Appendix 1 of this paper.

[§] "Draft Economic Impacts Assessment for Regulation of Ozone Emissions from Indoor Air Cleaning Devices". California Air Resources Board, Research Division. Page 11-12. http://www.arb.ca.gov/research/indoor/aircleaners/2276_econ_section_6-14.pdf. (June 14, 2007)

[**] "AB 2276 Air Cleaner Regulation" http://www.arb.ca.gov/research/indoor/aircleaners/aircleaners.htm (Last updated August 18, 2008 and site visited on September 18, 2008)

Table 1: Annual Sales by Device and Level of Ozone Emission

Classification by Type of Device	Annual Sales Estimate
Portable Indoor Air Cleaning Devices (IACD)	1,760,000 to 2,200,000
Ozone Generators (intentional)	317,000 to 396,000
Byproduct Devices	1,091,000 to 1,364,000
BP High Emitter	*218,000 to 273,000*
BP Low Emitter	*873,000 to 1,091,000*
Mechanical Filtration	352,000 to 440,000
Classification by Level of Ozone Emission	
Ozone Generating Air Cleaner Devices (OGAC) (1)	1,408,000 to 1,760,000
OGAC that may exceed UL 867 (2)	535,000 to 669,000
OGAC that may not exceed UL 867 (3)	873,000 to 1,091,000
De Minimis Levels (4)	352,000 to 440,000

(1) OGAC is the sum of intentional ozone generators and byproduct devices
(2) OGAC that may exceed UL 867 is the sum of intentional ozone and BP high emitters.
(3) OGAC that may not exceed UL 867 includes BP low emitters.
(4) De Minimis includes mechanical filtration devices.

b. Life Expectancy

While no good product life source could be found for portable air purifiers, ozone generating air cleaner machines typically do not come with a warranty and for devices that have a warranty, the warranty typically covers a period of no more than five years.* Moreover, a California survey found that most ozone generating air cleaner devices purchased were less than four years old, but that 18% were more than five years old. Based on this information, a reasonable estimate for the life expectancy of an ozone generating air cleaner device may be about five years.

c. Estimated Number of Devices in Use and Exposed Population

CPSC staff estimated the number of portable indoor air cleaning devices in use by multiplying the estimate for annual sales by a five year expected product life. To estimate the number of households with a device note that approximately 30% of households that own an air cleaning device own more than one device. Therefore, the number of households that own an IACD was estimated by dividing the number of devices in use by 1.3. These estimates are presented in Table 2.

* The warranty estimate is based on EC staff research of the OGAC device market.

Table 2: Number of Devices in Use and Household Ownership

Classification by Type of Device	Estimate of Number in Use	Estimated Number of Households that Own a Device
Portable Indoor Air Cleaning Devices (IACD)	8.8 to 11.0 million	6.8 to 8.5 million
Ozone Generators (intentional)	1.6 to 2.0 million	1.2 to 1.5 million
Byproduct Devices	5.5 to 6.8 million	4.2 to 5.3 million
BP High Emitter	1.1 to 1.4 million	0.8 to 1.1 million
BP Low Emitter	4.4 to 5.5 million	3.4 to 4.2 million
Mechanical Filtration	1.8 to 2.2 million	1.4 to 1.7 million
Classification by Level of Ozone Emission		
Ozone Generating Air Cleaner Devices (OGAC)	7.0 to 8.8 million	5.4 to 6.8 million
OGAC that may exceed UL 867	2.6 to 3.4 million	2.0 to 2.6 million
OGAC that may not exceed UL 867	4.4 to 5.5 million	3.4 to 4.2 million
De Minimis Levels	1.8 to 2.2 million	1.4 to 1.7 million

(1) OGAC is the sum of intentional ozone generators and byproduct devices
(2) OGAC that may exceed UL 867 is the sum of intentional ozone and BP high emitters.
(3) OGAC that may not exceed UL 867 includes BP low emitters.
(4) De Minimis includes mechanical filtration devices.

The estimate of the number of households with a device can be used to derive an estimate of the potentially exposed population. Based on the American Community Survey (ACS), the average household size is 2.61. Therefore, the number of persons living in a house with an IACD may be estimated by multiplying the number of households that own a device by the average household size, which yields the results presented in Table 3.*

* Note that because some intentional ozone generators may have an automatic shutoff mechanism, Table 3 may overestimate the numbers of individuals exposed to ozone levels above those specified in the UL 867 standard.

Table 3: Population Living in Household Where an IACD is Present

Classification by Type of Device	Estimate of Population Living in Household with an IACD
Portable Indoor Air Cleaning Devices (IACD)	17.7 to 22.1 million
Ozone Generators (intentional)	3.2 to 4.0 million
Byproduct Devices	11.0 to 13.7 million
BP High Emitter	2.2 to 2.7 million
BP Low Emitter	8.8 to 10.9 million
Mechanical Filtration	3.5 to 4.4 million
Classification by Level of Ozone Emission	
Ozone Generating Air Cleaner Devices (OGAC) (1)	14.1 to 17.7 million
OGAC that may exceed UL 867 (2)	5.3 to 6.7 million
OGAC that may not exceed UL 867 (3)	8.8 to 10 .9 million
De Minimis Levels (4)	3.5 to 4.4 million

(1) OGAC is the sum of intentional ozone generators and byproduct devices
(2) OGAC that may exceed UL 867 is the sum of intentional ozone and BP high emitters.
(3) OGAC that may not exceed UL 867 includes BP low emitters.
(4) De Minimis includes mechanical filtration devices.

Use Patterns and Household Characteristics

Little data exist that identify the demographics of consumers who purchase and use ozone generating air cleaners. Unless noted, the information regarding consumer usage patterns comes from a California survey.*

a. Household Factors

- Households who own air cleaners typically report a higher annual household income than households that do not own an air cleaner.
- Most households that own an air cleaner are composed of two adults.
- Approximately one-third (37%) of all households who own an ozone generating air cleaner have at least one child. This percentage compares similarly with Department of Census data that estimates that 38.6% of Californian households and 34.6% of United States households have at least one person under the age of 18 years in residence.†
- Approximately 31% of households with an ozone generating air cleaner own more than one device.
- Most ozone generating air cleaners currently in use were sold within the past two years.

* "Survey of the Use of Ozone-generating Air Cleaners by the California Public" Piazza, Thomas, Robert H. Lee and Jacqueline Hayes. ARB Contract Number 05-301. January 2007 (http://www.arb.ca.gov/research/apr/past/05-301.pdf)

† 2006 American Community Survey. Department of Census. *Households with one or more people under 18.*

b. Reason for Ownership

The most common reasons given for purchasing an ozone generating air cleaner include:

1) Remove allergens/person in the household has asthma
2) Remove dust
3) Concern over indoor air quality
4) Remove pet dander
5) Remove mold
6) Chemical contaminants.

Note that respondents were prompted with possible reasons why they purchased their ozone generating air cleaner and were allowed to provide multiple reasons. Prompting respondents may have introduced a bias in the results.

Other sources back the California survey findings. Health was the primary factor for the purchase, according to respondents of one manufacturer's survey in 1995.[*]

c. Frequency and Duration of Use

- Most owners of ozone generating air cleaners use the device year round and most owners use the machine daily.
- The survey found that 17% of ozone generating air cleaner owners no longer use their machine. The most common reasons given for not using the machine include that it is no longer needed, it doesn't seem to work, and it is too noisy.
- Air cleaners are most often used in either the master bedroom or the living room.

Summary

EC staff estimates that there are approximately 1.4 to 1.8 million OGACs sold annually and that 535,000 to 669,000 may emit levels of ozone in excess of levels specified in the UL 867 standard. Collectively, with a product life expectancy of five years, there could be approximately 7.0 to 8.8 million OGAC devices currently in use. EC staff estimates that there are approximately 5.4 to 6.8 million households and 14.1 to 17.7 million people that may live in a household where an OGAC device is present. Of those living in a household with a device, 5.3 to 6.7 million people may be exposed to ozone levels above the levels specified in UL 867.

The households that own ozone generating air cleaners typically run the device all day, every day. Some households own more than one device. Household ownership of air cleaning devices is positively correlated with income and most devices that are in current use were purchased within the past two years. Lastly, according to survey respondents, health related concerns are a primary factor behind the purchase of indoor air cleaning devices.

[*] Chapter 4: Factors to Consider before Using/Buying an Air Cleaner" American Lung Association. (http://www.lungusa.org/site/pp.asp?c=dvLUK9O0E&b=39310)

Appendix 1: CA survey estimate of air cleaner device ownership

This explains data taken from "Survey of the Use of Ozone-generating Air Cleaners by the California Public".

Summary of Responses

- 12,008 telephone numbers called
- 9,383 numbers confirmed to be households
- 2,019 completed the interview
- 284, or 14 percent of survey respondents own or have used a portable indoor air cleaner device (IACD) within the past 5 years.

Type of IACD	Response	Percentage
Intentional	46	16.2%
Byproduct	158	55.6%
No Ozone	51	18.0%
Unclassified	29	10.2%
Total	284	

Please note that the proportion of IACD that are classified either as intentional or as an unintentional by-product ozone producer within the study is vastly higher than what Consumers Union estimates.* Notwithstanding, this section will proceed using the findings of the study and provide an estimate of domestic ownership of ozone generating air cleaner.

By disaggregating the "unclassified" responses, the following indicates the percentage of IACD ownership by product type.

Type of IACD	Response	Percentage
Intentional	46	18.0%
Byproduct	158	62.0%
No Ozone	51	20.0%
Total	255	

Therefore, approximately 80 percent (204 of 255) of all air purifiers purchased or used by households within the past five years produce an ozone level greater than de minimis concentrations. No alternative source of data could be found to either verify or contradict the validity of these estimates. Also note that the survey relied on the respondent identifying the type of IACD owned/used and for various reasons the consumer may be unable to provide reliable information.

* Consumers Union, 2005c. "New concerns about ionizing air cleaners". *Consumer Reports*, May: 22-25.

Appendix C

UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Memorandum

Date: September 25, 2008

TO: Treye A. Thomas, Ph.D.
Division of Health Sciences

THROUGH: Hugh McLaurin, Associate Executive Director
Directorate for Engineering Sciences

Robert B. Ochsman, Ph.D., Director
Division of Human Factors

FROM: Catherine A. Sedney, Engineering Psychologist
Division of Human Factors

SUBJECT: Consumer Use of Portable Indoor Air Cleaning Devices (IACDs)*

Background

There are three general types of portable indoor air cleaning devices (IACDs). The first are referred to as "ozone generators" because they function through the intentional production of ozone. These products produce varying amounts of ozone during operation and some, which can produce dangerous levels of ozone, are intended for use in unoccupied areas. The second type includes ionizers and electrostatic precipitators that typically produce small amounts of ozone as a by-product (Jakober & Phillips, February, 2008). The third type function solely by drawing air through a filter and produce negligible amounts of ozone.

The State of California has banned IACDs with ozone emissions exceeding 50 parts per billion (ppb), the U.S. Food and Drug Administration's (FDA) limit for medical devices. In response to concerns raised by consumer advocacy groups, state health departments, and other entities, CPSC Health Sciences Division staff (HS) pursued a contract to evaluate whether the 50-ppb limit is adequate to protect consumers from exposure to air cleaners that produce ozone. Following completion and peer review of the contract work product, HS prepared a staff report of the work (Hatlelid & Thomas, draft dated 9/26/2006) and posted it for public comment. Comments received raised concerns regarding possible negative health effects among sensitive groups* and generated questions regarding the characteristics of the user population and typical use patterns for these products. Human Factors (HF) staff was asked to respond to questions (see

* In terms of ozone exposure, the sensitive population is not well-defined (cf. Shaughnessy, 2006). Per EPA (2003), people with asthma are "the only segment of the population that has been identified to be the most acutely responsive to ozone exposure….Individuals with chronic lung diseases characterized by impaired lung function may theoretically be at higher risk since even small additional decrements in lung function could result in disproportionate effects. The extent to which this is true is not known." For this report, "sensitive" is defined broadly as those with respiratory conditions who may be affected by exposure to ozone emissions.

Attachment A) regarding use patterns for IACDs and the demographics and time activity/use patterns for consumers who purchase them.

HF staff identified only two sources of detailed information regarding consumer use of portable air cleaners of any type. The first is a phone survey of portable air cleaner owners in California ("the CA survey"; Piazza, Lee, & Hayes, 2007). The work, conducted for the California Air Resources Board (CARB) and the California Environmental Protection Agency, is based on a list-assisted random-digit dialing sample of 9,383 California phone numbers. Of these, 2019 were confirmed households for which respondents granted an interview. The authors reported that approximately 14% (n = 284) of the respondent households owned a portable room air cleaner. Two percent owned products that intentionally produce ozone, and approximately 8% owned devices that produce ozone as a by-product. As discussed in subsequent sections, the report provides information on the demographics of California households in which air cleaners are used, why they were purchased, and how they are used. Among the important limitations of the study are that the respondent household sample (n = 2019) did not closely match the California population with respect to ethnic and racial identification, and that relative to the California public, those with incomes above $75,000 were overrepresented. The results regarding IACDs may not reflect the characteristics and behavior of air cleaner purchasers as a group, either in California or more generally, because of the inherent limitations of phone survey research (e.g., trends toward exclusive use of cell phones; low response rate, 21.6% in this instance; self-selection; and self-report bias). It does provide, however, relevant information from a large sample of users.

The second source is the Commission's database of in-depth investigation reports (INDP), which detail incidents that may indicate a product-related hazard. HF staff searched the database for reports involving "air purifiers" (product codes 307 and 2473) that occurred between 1/1/1998 and 10/31/2007. The results include all three types of portable air cleaners. Forty-two in-depth investigation reports (IDIs) were identified. One report involved an "air freshener" and was deemed out of scope based on details of the product description. A second report detailed original use of the product that differed from its use at the time of the incident, providing two distinct sets of information. Thus, 41 in-scope reports yielded a dataset reflecting 42 cases of product use. One case involved ozone poisoning. The rest concerned products that caught fire or overheated. Unlike the CA survey, the IDIs do not reflect a randomly selected sample of incidents or product users, and the information they contain was collected for purposes unrelated to the project. The quantity and quality of relevant data they include varies widely, and many reports are missing data for variables of interest. The value of the reports is that they provide detail on use scenarios among a group of consumers outside California for comparison to the CA survey. Because of the anecdotal nature of the data and the small number of cases, HF staff did not categorize the incidents or use data by type of air cleaner.

IACD Use Patterns, User Demographics, and User Time-Activity Data

What are the overall use patterns, including frequency and duration of use, location of IACDs within the residence, and proximity of IACDs to users [among healthy individuals] for the "typical consumer" (50th percentile) and 95th percentile "worst case scenario" for these devices?

For this purpose, HF staff defined “typical” as the most frequent response among the sample users. Among both the CA survey (68%) and IDI (32/42) respondents, most used only one air cleaner. Around 80% of air cleaner owners in the CA survey used the products year-round; 80% used them daily; and most (57%-72% depending on number and type of product) used them continuously. Information on how frequently the product was used was not included in approximately one-quarter of the IDIs. Where it was specified, continuous use (that is, turning off the product only for cleaning or when the home was unoccupied for extended periods) was most common (24/42), followed by daily intermittent use (6/42). Given the high proportion of consumers reporting daily and continuous use, there is no meaningful distinction between 50th and 95th percentile use for those using only one air cleaner.

Thirty-one percent of respondents to the CA survey reported owning two, three, or more air cleaners. Among the IDI respondents, seven of forty-two owned two, and one respondent owned three; one respondent received a small (7.75” x 2.50” x 2.00”) plug-in unit free with each of two full-size air cleaners he purchased, for a total of four. This subset, that is, owners of multiple air cleaners, may be more appropriately termed 95th percentile users because they may be exposed to air cleaners operating continuously in more than one location within the residence.

Consistent with the use of a single air cleaner, most respondents reported that specific areas of the home were treated, rather than the entire residence.[*] A bedroom was the most frequently reported room where an air cleaner was placed. Among the CA survey respondents, 40% reported use in the “master bedroom” and 9% in a “child’s room.” The second most common place, at 27%, was the living room. The proportions were similar among the IDI respondents, with 19 reporting use in a bedroom and 11, a living room. Other locations within the home reported by both survey and IDI respondents included the kitchen, office or den, family room, and basement.

The CA survey contained no data regarding the proximity of the air cleaner to residents during use. The IDIs provided specific information in only a few cases: approximately three feet from a bed, three feet from the foot of a bed, and approximately six feet from a crib. Less specific locations included on a nightstand, a refrigerator, kitchen counter or table, a filing cabinet or piece of furniture, and in a closet with the doors open.

What are the demographics of consumers who purchase IACDs (socioeconomic status, geographic location, reason for purchase, and exposure of consumers with a respiratory condition)?

The authors of the CA survey reported that air cleaner ownership was more frequent among higher-income households (≥ $75,000), less frequent among low-income households (<$35,000), and less frequent among minority households, regardless of income. Nearly two-thirds (62%) of households with air cleaners included no children, and 58% consisted of two adults. Although age data were collected, the age distribution of respondents was not reported.

[*] Exceptions include small residences, such as a one-bedroom apartment, in which one unit presumably may affect the entire living space.

The IDIs included no data on variables such as household income and ethnicity of respondents. The type of residence was included in most reports; whether the home was owned or rented, however, was generally not specified. Two reports, one involving a nursing home and the other a jewelry shop, were not relevant, and as indicated previously, one household accounted for two sets of use information. Among the remaining 39 cases, 22 of the residences appeared to be or were described as single-family homes, two as duplexes, three as apartments, and two as mobile homes; the type of residence was unspecified in ten cases.

The age of the respondent was typically included in the IDIs as a coded variable unless the victim, a child for example, was someone other than the respondent; narrative descriptions often provided ages of others in the household. In 15 of the IDIs, which included the incidents that occurred in a shop and a nursing home, no ages were specified. Seven reports mentioned minor children. When age was given, most respondents (20) were over 40 (44 to 93 years).

The IDIs comprised respondents in 19 states. Incidents occurred in all regions of the country as defined by the U.S. Census Bureau[*], but the largest number (17) occurred in the Midwest. The regions and states associated with the incidents are tabled below.

Table 1. IDI incidents by region and state.

Region	# of IDIs	States
West, Pacific	2	WA (2)
West, Mountain	2	UT (1) CO (1)
Midwest, West North Central	1	IA (1)
Midwest, East North Central	16	WI (4) MI (4) IL (5) IN (2) OH (1)
South, West South Central	5	OK (1) TX (2) LA (2)
South, East South Central	1	TN (1)
South, South Atlantic	6	NC (3) FL (3)
Northeast, Middle Atlantic	6	NY (3) PA (2) NJ (1)
Northeast, New England	2	NH (1) CT (1)

The CA survey explored the reasons for purchase of an air cleaner, and respondents answered yes or no to each of several categories. Fifty percent reported that the purchase, regardless of type, was prompted by the presence of someone in the home with allergies or asthma. Six percent responded in the affirmative to the category "other health condition."[†] Thirty-five

[*] www.**census**.gov/geo/www/**us**_regdiv.pdf

[†] Although the survey called for the "other health condition" to be specified, those data were not reported.

percent of respondents answered in the affirmative to the categories "remove dust" and "concern over indoor air quality." The remaining categories tended to overlap with the issues of health, cleanliness, and air quality (e.g., "remove pet dander," "remove mold/bacteria," "chemical contaminants," "control tobacco smoke," etc.) and were cited by respondents much less frequently. Beyond use of the term "someone in the home," the survey report included no information on the number of household members with a health condition.

In 22 of the IDIs, no specific reason was reported for the purchase of the product. Health conditions were cited in ten cases, and non-health-related reasons in nine cases. Reasons for purchase that were unrelated to a particular health condition included to remove odors, tobacco smoke, or dust, and a source of "white noise" to help a child or adult sleep. Six respondents specified allergies or asthma; other health-related conditions included emphysema and pneumonia, and one respondent had had a laryngectomy. When health was reported as the reason for purchase, one member of the household was affected.[*]

Although a significant portion of IACD purchases are reportedly motivated by health concerns, it is unknown what proportion of those exposed to them comprise individuals who suffer from a respiratory condition that may be affected by ozone emissions. Among the CA survey respondents, 50% attributed the use of an air cleaner specifically to someone in the household suffering from asthma or allergies,[†] and 6% reported "other health condition," presumably one affected by air quality, as the reason. These two health-related categories may overlap because respondents could choose as many answers as applied to their purchase. Therefore, one can state with certainty only that half the survey respondents reported that they purchased and used an air cleaner because of allergies or asthma. In the small sample of IDIs that included the reason for purchase, a similar proportion of respondents cited specific conditions that, despite the small numbers, encompassed a broader range of specific respiratory conditions.

These sources provide a basis to estimate that about 50% of households that have air cleaners purchased them to help with specific health conditions. This estimate can be used to gauge the sensitive population exposed to air cleaners. Assuming: (1) that the number of persons per household is similar between those purchasing IACDs for specific health reasons and those purchasing them for other reasons, and (2) that *all* members of the former are afflicted, would yield an estimate that 50% of those exposed to indoor air cleaners may have a respiratory condition. Clearly, however, not all members of a household would be affected. The details reported in the IDIs suggest that, rather than the maximum per household, it is more realistic to use the minimum number of one sensitive member per household while acknowledging that the true per-household number, on average, would be somewhat higher because some households would include more than one sensitive resident. EC staff estimates that the number of U.S. households where portable IACDs are used may range from 6.8 to 8.5 million, but is cautious about these estimates because of the limits of the CA survey (Peternel, September 18, 2008). However, the estimates provide the only available basis to approximate the population of

[*] The ten households consisted of 36 people, and ranged from two to ten people per household.
[†] Asthmatics and respiratory allergy sufferers are not independent groups, as asthma is associated with allergic response to airborne allergens. Those with respiratory allergies, such as allergic rhinitis (hay fever) constitute a broader population, members of which may or may not suffer from asthma.

individuals who suffer from a respiratory condition and are exposed to indoor air cleaners. If half the *households* with IACDs have them for health reasons, and at least one affected *person* per household is assumed, a ballpark estimate of those with respiratory conditions who are exposed to portable IACDs is 3.4 million to 4.3 million people.

Even this minimum figure could be a conservative estimate of the sensitive population *currently* exposed to IACDs. Work on the CA survey was completed in October 2006. It included residents who had purchased air cleaners in the previous five years, and 29% of respondents with air cleaners no longer used them at the time of the survey. The overlap among those households in which the products were purchased for health reasons and those which no longer use them cannot be determined. Some subset of this figure represents those who currently may be exposed to potentially hazardous ozone levels from air cleaners. Any estimate of that subset may be inflated. Because of increased concern regarding ozone, and the legislation in California, it is possible that the air cleaner industry has undergone changes resulting in products that have reduced ozone emissions (cf. Jakober & Phillips, February, 2008). Additionally, publicity about the potential hazards of ozone-producing air cleaners in recent years (e.g., Consumers Union, 2005; DeNoon, 2006; Reuters, 2008) may have influenced the purchase and use of these products in ways that could reduce the exposure of sensitive groups to air cleaner ozone emissions.

Time activity/use pattern: How long would someone be exposed to treated air from an IACD ("reasonable worst case" [healthy individuals], "95th percentile worst case" [healthy individuals], and "worst case" [sensitive individuals])?

The tables below, which report time-use patterns, are adapted from the U.S. Environmental Protection Agency's (EPA) *Exposure Factors Handbook* (U.S. EPA., 1997). The data were collected by means of a diary-based telephone survey of U.S. residents sponsored by the EPA (Tsang & Klepeis, 1996*). Table 2 presents the cumulative hours spent at home in a bedroom reported by respondents in various groups. Table 3 presents the cumulative hours respondents reported spending indoors at a residence.

The most common residential use of IACDs entails one device operating continuously in a bedroom. This appears a logical basis for selection of "worst case" scenarios because bedrooms typically are smaller than common-use areas of the home, and are more likely to be enclosed (i.e., with the door fully or partly closed, and thereby potentially limiting airflow). Ozone concentration decreases with distance away from the emission source (Babich, April 14, 2008). HF staff's assessment for this section assumes that ozone emissions at the proposed rate in a bedroom would have limited impact on other areas of the typical residence, a single family home. By extension, HF staff defines the requested "reasonable worst case among healthy individuals" based on the subgroup which spends the highest proportion of time in a bedroom. As can be seen in Table 2, on average, children aged one to four years spent 12.37 hours in a

* The survey, known as National Human Activity Pattern Survey (NHAPS), collected data for 9,386 respondents in the 48 contiguous United States via minute-by-minute 24-hour diaries between October 1992 and September 1994. Participants' responses were weighted according to geographic, socioeconomic, time/season, and other demographic factors to ensure that results were representative of the U.S. population (U.S. EPA, 1997).

bedroom, more than any group, and may represent a "reasonable" worst-case timeframe for the "typical" use scenario. The 95th percentile exposure in that subgroup, again for the most common use scenario, was 16.50 hours.

As described earlier, somewhat less than a third of the CA survey respondents reported using two, three, or more IACDs, which potentially exposed them to ozone emissions in multiple areas of the home. It seems appropriate to estimate 50th and 95th percentile "worst case" exposures based on this subset of users, and in terms of total time spent in the residence. As can be seen in Table 3, on average, young children again spent the longest time inside a residence at 20.19 hours, and are followed closely by adults over age 64, at 19.58 hours.

Table 2. 24-Hour Cumulative Number of Hours* Spent at Home in the Bedroom

				Percentiles					
Category	**Group**	**Mean**	**Stdev**	**5th**	**25th**	**50th**	**75th**	**95th**	**99th**
All		**9.39**	**3.08**	**5.00**	**7.67**	**9.00**	**11.00**	**14.67**	**19.02**
Gender	Male	9.16	3.05	4.75	7.50	9.00	10.67	14.33	18.25
Gender	Female	9.57	3.09	5.20	7.83	9.25	11.00	15.00	19.75
Age (years)	**1-4**	**12.37**	**2.78**	**8.15**	**10.58**	**12.33**	**14.00**	**16.50**	**20.00**
Age (years)	5-11	11.15	2.71	7.25	10.00	11.08	12.33	15.25	19.00
Age (years)	12-17	10.60	3.51	2.75	9.03	10.75	12.50	16.17	20.17
Age (years)	18-64	8.88	2.88	4.92	7.33	8.67	10.17	13.67	18.50
Age (years)	**> 64**	**9.18**	**2.87**	**5.25**	**7.92**	**9.00**	**10.17**	**14.00**	**19.00**
Asthma	No	9.35	3.05	5.00	7.67	9.00	10.92	14.50	19.00
Asthma	**Yes**	**9.90**	**3.36**	**5.00**	**7.92**	**9.67**	**11.50**	**15.77**	**22.12**
B/E	No	9.38	3.07	5.00	7.67	9.00	11.00	14.67	19.02
B/E	**Yes**	**9.50**	**3.20**	**4.90**	**7.50**	**9.25**	**11.00**	**15.00**	**18.50**

*Converted from original data in minutes.
B/E: Bronchitis/Emphysema
Adapted from: U.S. EPA. Exposure Factors Handbook Revised. (1997). Volume III, Chapter 15: *Activity Factors* (Table 15-115). Retrieved 1/11/08 from http://www.epa.gov/ncea/efh/.

Table 3. 24-Hour Cumulative Number of Hours* Spent Indoors in a Residence (all rooms)

				Percentiles					
Category	**Group**	**Mean**	**Stdev**	**5th**	**25th**	**50th**	**75th**	**95th**	**99th**
All		**16.69**	**4.59**	**9.58**	**13.25**	**16.42**	**20.58**	**24.00**	**24**
Gender	Male	15.77	4.56	9.00	12.50	15.00	19.33	23.83	24
Gender	Female	17.47	4.46	10.33	14.00	17.50	21.33	24.00	24
Age (years)	**1-4**	**20.19**	**3.65**	**13.25**	**17.75**	**21.00**	**23.50**	**24.00**	**24**
Age (years)	5-11	16.75	3.71	11.43	14.08	16.25	19.42	23.54	24
Age (years)	12-17	16.16	4.03	9.75	13.53	15.83	19.25	23.42	24
Age (years)	18-64	15.80	4.55	9.00	12.50	15.00	19.42	23.80	24
Age (years)	**> 64**	**19.58**	**3.82**	**12.67**	**17.17**	**20.17**	**22.92**	**24.00**	**24**
Asthma	No	16.65	4.57	9.60	13.25	16.33	20.50	24.00	24
Asthma	**Yes**	**17.12**	**4.74**	**9.25**	**13.75**	**17.08**	**21.00**	**24.00**	**24**
B/E	No	16.63	4.58	9.58	13.25	16.25	20.50	24.00	24
B/E	**Yes**	**17.84**	**4.56**	**9.75**	**14.46**	**18.50**	**21.54**	**24.00**	**24**

*Converted from original data in minutes.
B/E: Bronchitis/Emphysema
Adapted from: U.S. EPA. Exposure Factors Handbook Revised. (1997). Volume III, Chapter 15: *Activity Factors* (Table 15-131). Retrieved 1/11/08 from http://www.epa.gov/ncea/efh/.

There is a ceiling at the 95th percentile for time spent in a residence. In a home where multiple IACDs are in use, all groups potentially would be exposed to some extent, based on the number and location of the devices, for 24 hours. Clearly, the worst-case exposure time for sensitive populations would be the same.

Summary and Conclusions

Although quite limited, the data derived from Commission investigation reports does not appear to diverge in any notable way from the systematically collected data reported from the survey of air cleaner owners in CA. Although the CA survey data cannot be assumed representative of air cleaner owners in the U.S., it provides a basis for the characterization of general IACD use pending collection of data from a national sample of users.

The "typical" or "50th percentile" use of IACDs seen in the two sources involves the use of one product, most often in a bedroom, operating continuously. At the high end of the distribution are consumers who operate multiple air cleaners continuously in bedrooms and one or more common-use areas of the home, such as the living room. The limited information available suggests that air cleaners typically are placed where they will be at least a few feet away from someone in the room.

Demographically, households where air cleaners are used appear to be more likely to consist of adults, tend to have higher incomes, and perhaps to be single-family residences. It is possible that age is a factor in air cleaner use, given that adult-only households predominated in the CA survey (62%), and that IDI respondents tended to be over 40. That cannot be confirmed without additional data from the survey.

One-half of all owners in the CA survey specifically report asthma or allergies as their reason for purchasing an air cleaner. Although very small in number, and anecdotal in nature, of those reporting their reason for purchase among the IDI respondents, a similar proportion cited specific health-related concerns. However, it is unlikely that all members of the household are affected. Given the limited information available, it is realistic to gauge the sensitive population based on a minimum number of persons per household in that proportion of households that identified specific health concerns. Based on EC estimates of households with air cleaners and an assumption of a minimum value of one person per household, 3.4 million to 4.3 million people exposed to IACDs may have respiratory conditions. As an indicator of current use, this estimate may be conservative, as would be any approximation based thereon of the sensitive population currently exposed to ozone levels that are potentially hazardous to them. Nearly a third (29%) of the CA respondents no longer used their air cleaner at the time of the survey, which was completed in 2006. Further, market changes and publicity regarding ozone-producing air cleaners may have served to reduce the exposure of sensitive groups to these products.

Estimates of "reasonable worst case," "95th percentile worst case," and "worst case" exposure durations can be characterized based on single versus multiple IACD use and national time-use data. The typical pattern is use of one IACD in a bedroom. The average child aged one through four spends 12.37 hours in a bedroom, and may represent the worst "reasonable" case; the 95th percentile counterpart spends 16.50 hours in a bedroom. For households using multiple devices, suggesting a higher and perhaps more consistent exposure throughout the time indoors in a residence, the average time is 20.19 hours for a child aged one through four, and 19.58 hours for the average adult over age 64. The estimated 95^{th} percentile exposure time in a residence for all groups, representing a worst-case duration for both healthy and sensitive individuals, is 24 hours.

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Attachment A

Ozone-Generating Air Cleaner (IACD)
Economic Analysis and Human Factors

Question: If we conduct a risk assessment for the OCAC what inputs would we use for the use/exposure scenario

1. What are the overall use patterns for these devices?
    a. Describe the use pattern of the "typical consumer" (50^{th} percentile)
    b. Use pattern of a 95^{th} percentile worst case scenario
    c. Assume that device is plugged in and remains on?
        i. Time-activity pattern
        ii. Where is device located (bedroom, living room)
            1. Is entire home treated or only specific rooms?
        iii. Location of device versus consumer location (distance from couch, bed, etc.)

2. What are the demographics of consumers who purchase IACD
    i. Socioeconomic status
    ii. Geographic location
        1. Impacts potential ambient ozone levels
    iii. Are devices purchased for someone with a respiratory disease
        1. Percentage of population exposed to IACD that has a respiratory condition

3. Time activity/use pattern
    a. How long would someone be exposed to treated air from an IACD
        i. 16 (e.g., young school age child 3 pm to 7 am as reasonable worst case)
        ii. 20 (95^{th} percentile)
        iii. 24 (Worst case e.g., elderly with no/limited mobility)

Appendix D

UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Memorandum

Date: April 14, 2008

TO : Treye A. Thomas, Ph.D., Project Manager for Air Cleaners

THROUGH : Mary Ann Danello, Ph.D., Associate Executive Director for Health Sciences
Lori E. Saltzman, M.S., Director, Division of Health Sciences

FROM : Michael A. Babich, Ph.D., Chemist, Division of Health Sciences

SUBJECT : Modeling ozone levels in residences with ozone-generating air cleaners*

Introduction

Portable air cleaners are small appliances used to remove particles or other pollutants from the air in a room or area of a residence. Some air cleaners may emit ozone either intentionally or as a by-product. Ozone is a chronic respiratory toxicant (reviewed in EPA 2006). As air cleaners may be used by consumers with respiratory conditions (Piazza et al. 2007; Sedney 2008), it is especially important to limit ozone emissions from air cleaning devices. Underwriters Laboratories (UL) has developed a voluntary standard to test and limit ozone emissions from air cleaners (UL 2000). The standard is currently being revised. The purpose of this memorandum is to consider whether the UL standard is adequate to maintain ozone levels at acceptable levels during reasonably foreseeable conditions of use.

The U.S. Consumer Product Safety Commission (CPSC) staff has recommended a maximum indoor ozone level of 50 parts-per-billion (ppb). Recently, the adequacy of the 50 ppb maximum level was reviewed (Shaughnessy 2006). The U.S. Environmental Protection Agency (EPA) has set an 8-hour limit of 80 ppb in ambient air (EPA 2006), and recently decided to reduce the 8-hour limit to 75 ppb.

UL Standard

The UL 867 standard limits ozone emissions from air cleaners to a maximum of 50 ppb in a test chamber under conditions specified in the standard (UL 2000). Briefly, the total measured decay rate in the chamber, that is, the sum of the air exchange rate and reactive decay rate, must be at least 1.33 per hour. In addition, the ozone concentration is measured near the face of the air cleaner, at the point where the ozone concentration is at a maximum.

* This report was prepared by the CPSC staff; it has not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.

Methodology

Mass balance models (NRC 1981) were used to estimate indoor ozone levels in residences. One-zone, two-zone, and multiple-zone models were used. Steady state conditions were assumed, because air cleaners may be operated for several hours or continuously (Piazza et al. 2007; Sedney 2008). The one-zone model was used to model a bedroom, which represents a typical use scenario (see Figure 1) (Piazza et al. 2007; Sedney 2008). With the two-zone model, zone one was a bedroom containing the ozone source and zone two was the rest of the house. Some consumers may use multiple air cleaners in different rooms (Piazza et al. 2007; Sedney 2008). Thus, the multiple-zone model was used to model a scenario in which three ozone sources are operating simultaneously in three bedrooms. Other zones included a hallway and the rest of the house.

All of the models discussed here require the source strength (mg/h or cc/h) as a key input parameter (see Table 1 for conversion factors). However, the UL standard does not measure the source strength. Rather, it measures the steady-state ozone level in a test chamber under specified conditions. Thus, the first step in this analysis was to estimate the maximum source strength permitted by the UL standard (~4 mg/h or 2 cc/h). Second, the one-zone model was used to estimate the maximum source strength associated with 50 ppb ozone indoors. Third, the source strengths estimated in steps 1 and 2 were used to estimate indoor ozone levels. Both deterministic and probabilistic calculations were performed. Steps 2 and 3 were repeated for the two-zone and multiple-zone models. Only deterministic calculations were done for the multiple-zone model.

<u>One-Zone Model</u>

The ozone concentration in the one-zone model is given by:*

$$C = \frac{\frac{S}{V} + a \cdot C_0}{a + v\frac{A}{V}} \tag{1}$$

where: C, concentration, cc/m^3; C_0, ambient concentration, cc/m^3; t, time, h; S, source strength, cc/h; V, volume, m^3; a, air infiltration rate, v, deposition velocity, m/h; and A is the total surface area including furnishings, m^2. A/V is the surface-to-volume ratio, m^2/m^3.

Solving for S: $$S = V\left[C\left(a + v\left(A/V\right)\right) - a \cdot C_0\right] \tag{2}$$

The total surface area of the room (A) includes all exposed ceiling, floor, and wall surfaces, as well as all furnishings. Empirical measurements of total surface: volume ratios in residences are available, including data for bedrooms, kitchens, and other areas (Hodgson et al. 2004). A/V was found to vary by room volume (see Figure 2). The dependence of A/V on room volume

* All equations are derived in Appendix A.

makes it necessary to match A/V data to the volume of the room being modeled. To accomplish this, the total surface area-to-volume ratio (A/V) was modeled as a function of the surface area of the room envelope (E), that is, the area of the ceiling, floor, and walls only.

The empirical total surface area-to-volume ratio (A/V) was a linear function of calculated envelope surface-to-volume ratio (E/V):

$$R \equiv \frac{A/V}{E/V} = \frac{A}{E} \tag{3}$$

where: A, total surface area, m^2; E, envelope surface area, m^2; V, volume, m^3; and R, ratio of A to E.

The envelope surface area (E) depends, in turn, on the room volume V. Assuming that the room length and width are equal, E is given by (see Appendix):

$$E = 2\frac{V}{H} + 4H\sqrt{\frac{V}{H}} \tag{4}$$

where: E, envelope area, m^2; F, floor area, m^2; V, volume, m^3; and H, height, m.

The total surface area-to-volume ratio A/V was calculated by:

$$\frac{A}{V} = R\cdot\frac{E}{V} = R\cdot\left[\frac{2\frac{V}{H} + 4H\sqrt{\frac{V}{H}}}{V}\right] \tag{5}$$

where: A/V, surface-to-volume ratio, m^2/m^3; R, ratio of the total surface area (including furnishings) to the envelope surface area (ceiling, floor, and walls only); V, room volume, m^3; and H, room height, m.

The ratio R was estimated from the data presented in Hodgson et al. (2004). For simplicity, equation (5) assumes that the room length and width are equal. Changing the aspect ratio from 1:1 to 3:1, for example, would increase A/V by 5 to 10%, depending on the room size (not shown). This would have the effect of slightly underestimating reactive decay and, therefore, slightly overestimating indoor ozone levels.

The maximum source strength that would pass UL 867 is given by:

$$S = V\cdot C\cdot N_{App} \tag{6}$$

where: S, source strength, cc/h; V, volume, m^3; C concentration, cc/m^3; and N_{App}, net decay rate in the chamber, h^{-1}.

and where: $$N_{App} = a + v\frac{A}{V} \tag{7}$$

Two-Zone Model

The two-zone model may be described by two simultaneous equations:

$$C_1 = \frac{S + a \cdot C_0 \cdot V_1 + a_{12} \cdot C_2}{a_{12} + \left(a + v\frac{A_1}{V_1}\right)V_1} \tag{8}$$

$$C_2 = \frac{a \cdot C_0 \cdot V_2 + a_{12} \cdot C_1}{a_{12} + \left(a + v\frac{A_1}{V_1}\right)V_2} \tag{9}$$

where: C_1 and C_2, concentration in zones 1 and 2, respectively, cc/m^3; C_0, ambient concentration, cc/m^3; S, source strength, cc/h; V_1 and V_2, volume of zone 1 and zone 2, m^3; a, air infiltration rate, h^{-1}; a_{12}, inter-zone air exchange rate, m^3/h; v, deposition velocity, m/h; and A_1 and A_2, surface area of zones 1 and 2, m^2. The surface-to-volume ratios for each zone $(A/V)_i$ are calculated with equation (5).

These simultaneous equations were generally solved with a spreadsheet program (Microsoft Excel®). However, this approach was not compatible with the add-in program used for probabilistic calculations (@Risk©). Thus, it was necessary to solve the simultaneous equations by substitution. Substituting equation (9) into equation (8) gives:

$$C_1 = \frac{\dfrac{S + a \cdot C_0 \cdot V_1}{N_1} + \dfrac{a \cdot a_{12} \cdot C_0 \cdot V_2}{N_1 \cdot N_2}}{1 - \dfrac{(a_{12})^2}{N_1 \cdot N_2}} \tag{10}$$

where: $N_1 = a_{12} + (a + v\frac{A_1}{V_1})V_1$ and $N_2 = a_{12} + (a + v\frac{A_2}{V_2})V_2$ (11)

The source strength was calculated by solving equation (8) for S:

$$S = a_{12}\left(C_1 - C_2\right) + \left(a + v\frac{A_1}{V_1}\right)C_1 \cdot V_1 - a \cdot C_0 \cdot V_1 \tag{12}$$

Multiple-Zone Model

The multiple-zone model was used to model a scenario in which three ozone sources are operating simultaneously in three bedrooms (zones 1-3); no other indoor ozone sources are present. It was assumed that the bedrooms open onto a common hallway (zone 4) that opens onto the rest of the house (zone 5), e.g., living room, dining room, and kitchen (Figure 1). The hallway does not exchange air directly with the outside. For simplicity, the surface-to-volume ratios and deposition velocities of all rooms are assumed to be equal. The air infiltration rates of all rooms are assumed to be equal, except the hallway, which has a zero infiltration rate. The source strengths of the three ozone sources are also assumed to be equal. Based on these assumptions, the multiple-zone model is described by a set of five simultaneous equations:

$$C_1 = \frac{S + a \cdot C_0 \cdot V_1 + a_{14} \cdot C_4}{a \cdot V_1 + v \cdot A_1 + a_{14}} \tag{13}$$

$$C_2 = \frac{S + a \cdot C_0 \cdot V_2 + a_{24} \cdot C_4}{a \cdot V_2 + v \cdot A_2 + a_{24}} \tag{14}$$

$$C_3 = \frac{S + a \cdot C_0 \cdot V_3 + a_{34} \cdot C_4}{a \cdot V_3 + v \cdot A_3 + a_{34}} \tag{15}$$

$$C_4 = \frac{a_{14} \cdot C_1 + a_{24} \cdot C_2 + a_{34} \cdot C_3 + a_{45} \cdot C_5}{v \cdot A_4 + a_{14} + a_{24} + a_{34} + a_{45}} \tag{16}$$

$$C_5 = \frac{a \cdot C_0 \cdot V_5 + a_{45} \cdot C_4}{a \cdot V_5 + v \cdot A_5 + a_{45}} \tag{17}$$

where: C_i, concentration in the i-th zone, cc/m^3; C_0, ambient concentration, cc/m^3; S, source strength, cc/h; V_i, volume in the *i*-th zone, m^3; a, air infiltration rate, h^{-1}; a_{ij}, inter-zone air exchange rate between the *i*-th and *j*-th zones, m^3/h; v, deposition velocity, m/h; and A_i, total surface area in the *i*-th zone, m^2.

Probabilistic Calculations

Probabilistic calculations were performed with @Risk© 4.5. Each simulation consisted of 25,000 iterations. Wherever possible, discrete distributions (i.e., bootstrap approach) were used as input distributions. In some cases this involved the use of a set of observed values (e.g., room volumes). In other cases, percentiles (including 1st and 99th percentiles) were used (e.g., air infiltration rate). The deposition velocity was modeled as a lognormal distribution, as only summary statistics were available.

In performing probabilistic calculations with the two-zone model, the deposition velocity *v* and the ratio *R* (used to calculate the surface-to-volume ratio) were sampled independently for each zone, because, in principle, each room has its own characteristic deposition velocity and surface area. With the 2-zone model, zone 1 (bedroom) volumes were stratified by total (house) volume (Persily 2006), because average bedroom volumes increase with the total volume.

Probabilistic calculations were not performed with the multi-zone model.

Input Parameters

Distributions of air infiltration rates (h^{-1}) were from Murray and Burmeister (1995).* These distributions were derived from perfluorocarbon tracer (PFT) data for U.S. residences described by Koontz and Rector (1993). Data were reported as percentiles (1, 5, 10, 25, 30, 40, 50, 60, 70, 80, 90, 95, and 99), based on a total of 2,844 measurements. Data for all seasons and all regions of the U.S. were used. The mean infiltration rate was 0.76 h^{-1}, with a standard deviation of 0.88, and a median of 0.51 h^{-1} (see Table 2).

Ambient ozone concentrations (ppm or cc/m^3) were from EPA (2006, Vol. II, Table AX3-2). These data represent 24-hour average pooled outdoor ozone concentrations for all monitoring sites, May through September, 2000 through 2004. These were reported as percentiles (1, 5, 10, 25, 30, 50, 70, 75, 90, 95, and 99). Summary statistics for consolidated metropolitan areas (CSA's) and non-CSA's, which were roughly equal; were averaged. The mean ambient ozone level was 0.0335 ppm (cc/m^3), with a median of 0.0325, based on 345,506 measurements.

Deposition velocities were measured by Lee et al. (1999). Only summary statistics were reported. These were modeled as a lognormal (see Lee et al. 1999, Figure 1) distribution with a mean of 1.76 h^{-1} and standard deviation of 0.61 (N=43).

Distributions of total home volumes are from Murray (1997, Table 2). The distributions were derived from the U.S. Department of Energy (DOE) Residential Energy Consumption Survey (RECS) and other sources (Murray 1997). DOE RECS data for the heated volumes of all residences were used in this analysis. Volumes were reported as percentiles (1, 5, 10, 20, 25, 30, 40, 50, 60, 70, 75, 80, 90, 95, and 99). For all U.S. residences (N=7,000), the mean heated volume was 382 m^3, with a standard deviation of 242, and a median of 316 m^3. The volume of zone 2 (V_2) was the difference between the total home volume (V_t) and the zone 1 volume (V_1).

Murray (1997) reported the total bedroom volumes in a subset of homes (Los Angeles, CA), but did not report individual bedroom volumes. Therefore, bedroom (zone 1) volumes were estimated from data in Persily et al. (2006). Persily et al. described floor plans for residences that are considered representative of U.S. housing stock. Volumes for each room were calculated from the floor plans, tabulated, and stratified by house size into three strata, as described by Persily et al. Only detached, single-family homes were used for this analysis. There were a total of 114 bedrooms from 35 floor plans. Persily et al. assigned a statistical weight to each floor plan. The Persily et al. data were based, in part, on the DOE RECS data.

The statistical weights assigned to each floor plan were applied to each bedroom in that floor plan. The volumes were thus treated as weighted, discrete distributions. When using the 2-zone model, bedroom volumes were stratified into three groups by the total house volume, as

* Input data are tabulated in Appendix B.

described by Persily et al. (2006). Thus, the bedroom (zone 1) volume was dependent, in part, on the total volume. Volumes for "all" bedrooms were used with the one-zone model. Summary statistics were obtained by a bootstrap analysis of the weighted values. For all detached homes, the mean bedroom volume was 41.6 m^3 (SD=13.4) and the median was 38.1 (m^3) (N=114) (Table 2).

For the multiple-zone model, three bedrooms were assumed. The total house volume (316 m^3) is the median value for all homes (see above). The volumes of the three bedrooms—50, 30, and 20 m^3—are roughly based on the range (22 to 50 m^3) and mean (33.8 m^3) bedroom volumes for homes with less than 360 m^3 total volume (Persily et al. 2006).

The room volumes reported by Persily et al. (2006) are based on data from DOE RECS and the U.S. Census Bureau American Housing Survey (AHS). The total house volumes used in this analysis are from the RECS data only (Murray 1997). Unfortunately, distributions of bedroom and house volumes were not available from the same source. Murray did not report individual bedroom volumes. The set of floor plans described by Persily et al. included only three different total volumes (small, medium, and large); thus, it was not practical to use Persily's data to derive a distribution of total volumes. However, both the total volumes and bedroom volumes are based, at least in part, on the RECS data. Furthermore, both the RECS and AHS data are considered to be representative of the U.S. housing stock (Murray 1997; Persily et al. 2006). Therefore, it seems reasonable to assume that both data sets are roughly comparable and that it is appropriate to use them together.

The ratio R was calculated from published data (Hodgson et al. 2004, Figure 2). The mean ratio was 1.74, with standard deviation 0.37, median 1.81, and N=33. For the two-zone model, *R* was sampled independently for zones 1 and 2.

The interzone air exchange rate $a_{ij,}$ required by the two-zone and multiple-zone models, was modeled as a constant that was dependent on certain building characteristics. Two cases were modeled. With the bedroom (source room) door closed, a low interzone air exchange rate (2.5 m^3/h) was used. With the bedroom door open, a high interzone air exhange rate (500 m^3/h) was used. These were estimated as described by Shair (1982), using equation (18) and assuming a 1 to 2°C temperature difference between zones. The higher value may also represent a residence with a forced air heating/air conditioning system, which leads to rapid mixing between zones.

$$a_{12} = 189.29 \cdot Width \cdot Height^{1.5} \cdot \sqrt{|\Delta Temp|} \tag{18}$$

where: Width and Height, are the dimensions of the opening (m), and ΔTemp is the temperature difference between zones (C°).

Results

UL 867

UL 867 specifies a test chamber with a volume between 26.9 and 31.1 m^3 and a net apparent decay rate N_{App} of 1.33 h^{-1} (UL 2000). The maximum concentration in the chamber at steady-state is 0.050 cc/m^3 (ppm). If the background ozone concentration in the chamber is zero, then the maximum source strength is given by equation (6). Substituting appropriate values gives:

$$2.0 \text{ cc/h} = \left(30 \text{ m}^3\right) \cdot \left(0.050 \text{ cc/m}^3\right) \cdot \left(1.33 \text{ h}^{-1}\right) \tag{19}$$

Thus, the maximum source strength that can pass UL 867 is 2 cc/h (or 4.0 mg/h) (see Table 1).

One-Zone Model

The one-zone model was used to model a bedroom with an ozone-generating air-cleaning device. The bedroom exchanges air with the outdoors through air infiltration. A source strength of 2 cc/h (4/mg/h), the maximum allowed by UL 867, was assumed. Under average (median) input values, the estimated indoor ozone concentration was 10.9 ppb (Table 3). Various other inputs were also considered. For a number of "reasonable worst case" conditions, the indoor ozone level did not reach 50 ppb. However, the ozone level was about 80 ppb under extremely worst case conditions, that is, when all parameters were adjusted to maximize the indoor ozone level. Such extreme conditions are not likely to occur in real life.

The maximum source strength was calculated using probabilistic methods, using the input distributions described in Table 2. By this methodology, the median value of the maximum source strength was 10.7 cc/h (Table 4). The 5^{th} percentile value was 4.9 cc/h.

Source strengths of 2, 5, and 10 cc/h were used to estimate the indoor ozone level, using probabilistic methods. At a source strength of 5 cc/h, the indoor ozone concentration was less than 50 ppb in an estimated 95% of residences (Figure 3A; Table 5). At a source strength of 2 cc/h, the estimated ozone level was less than 50 ppb in more than 99% of homes.

Two-Zone Model

The two-zone model was used to model a bedroom with an ozone-generating air-cleaning device (zone 1) as part of a residence. Zone 2 is all other rooms. The bedroom exchanges air with the outdoors and the rest of the house. Two conditions were modeled—door closed and door open. The two-zone model was first used to estimate the maximum source strength, that is, the source strength associated with an indoor (zone 1) ozone concentration of 50 ppb. With the door closed, the median source strength was estimated to be 11.9 cc/h; the 5^{th} percentile value was 5.7 cc/h (Table 4).

Source strengths ranging from 2-to-10 cc/h were used to estimate the indoor ozone levels in residences. At a source strength of 5 cc/h and with the bedroom door closed, the median concentration in the bedroom was about 25 ppb, and the concentration was less than 50 ppb in

95% of homes (Figure 3B; Table 5). At a source strength of 2 cc/h, the maximum allowed by UL 867, the median concentration in the bedroom was 12.5 ppb, and the ozone level was less than 50 ppb in more than 99% of homes. For a given source strength, ozone levels in the bedroom were roughly equal to those with the 1-zone model. Average ozone levels in the rest of the house (zone 2) were several times less than the levels in the bedroom (Figure 4; Table 5). Comparison of Figures 2A and 2B, shows that with the bedroom door closed, the estimated ozone levels in zone #1 of the 2-zone model were nearly identical to the ozone levels in the one-zone model.

With the bedroom door open, there is more mixing of air between zones. Thus, the ozone levels decline in zone 1, while they increase in zone 2 (Figure 4; Table 5).

Multiple-Zone Model

The multiple-zone model was used to model the simultaneous use of three ozone sources located in three bedrooms in a residence. The bedrooms open onto a common hallway, which leads to the other rooms. The bedrooms doors were assumed to be closed. With a source strength of 2.0 cc/h, the maximum allowed by UL 867, the ozone concentrations in the bedrooms ranged from 10 to 16 ppb, with the highest level in the smallest bedroom (Table 6). With a source strength of 5.0 cc/h, the ozone concentration in all zones was below 50 ppb. At a source strength 7.0 cc/h, the ozone level in bedroom 3 was 50.1 ppb.

Discussion

Maximum Source Strength Allowed by UL 867

UL 867 requires that ozone measurements be made at the face of the air cleaner at a point where the ozone concentration is greatest. This requirement is intended to protect consumers who may position the air cleaner near their breathing zone (Mason 2007). Typically, pollutant concentrations near a point source are two-to-three times greater than concentrations elsewhere in the chamber. This was generally true for ozone generating air cleaners (Jakober and Phillips 2008; Mason 2007; Phillips and Jakober 2006), although in some cases the difference was greater. In tests performed for the California Air Resources Board (CARB), the ozone concentration at 2 inches from the device ranged from 1.4- to 22-fold greater than the ozone concentration at 24 inches (Jakober and Phillips 2008).

Measuring the ozone concentration near the source means that the average ozone concentration in the chamber is overestimated. While this is protective of human health, it complicates the analysis presented here. The first step in this analysis was to calculate the source strength that would lead to a chamber concentration of 50 ppb, that is, the maximum source strength allowed by the standard. If the measured concentration is 2-to-3-fold greater than the average chamber concentration, then the source strength will be overestimated by the same amount.

The maximum source strength allowed by UL 867 was calculated to be 2 cc/h or approximately 4 mg/h. UL 867 was designed to allow a maximum source strength of 4 mg/h (Mason 2007).

Maximum Source Strength in a Residence

The second step in this analysis was to estimate the maximum source strength consistent with 50 ppb ozone in a residence, specifically, a bedroom. This was accomplished by using single-zone and two-zone mass balance models. Probabilistic methods were applied to account for variability in the sizes and characteristics of U.S. residences. A source strength of 10-to-13 cc/h would lead to a concentration of 50 ppb in an average bedroom (Table 4). However, a source strength of 5-to-6 cc/h would be needed to keep the ozone concentration below 50 ppb in a broad range of homes.

Shaughnessy (2006) estimated that the maximum source strength in a residence would be from 14-to-26 mg/h, which is equivalent to 7-to-13 cc/h. Shaughnessy used a one-zone model with a range of room sizes from 15 m^3 to 40 m^3. He also assumed an air infiltration rate of 0.35 h^{-1}, deposition velocity of 1.76 m/h (compare Table 2), and an ambient ozone level of zero. His estimated maximum ozone levels of 7-to-13 cc/h are roughly comparable to the values estimated here (5-to-13 cc/h) (Table 4).

Ozone Concentrations in Residences

The third step in the analysis was to estimate the distribution of ozone levels in residences. It was assumed that the air cleaner would be located in a bedroom. The one-zone model was used to examine hypothetical "reasonable worst case" scenarios. "Reasonable worst case" is defined as an instance in which one or more, but not all, input parameters are set to extreme values. Under various reasonable worst case assumptions, the indoor ozone level was maintained below 50 ppb (Table 3). The recommended limit of 50 ppb was exceeded only when all of the parameters were set to extreme values.

Probabilistic methods were then applied to the one-zone model. With the source strength set to 5 cc/h, the ozone level would be below 50 ppb in about 95% of cases (Table 5). With a source strength of 2 cc/h (4 mg/h), the maximum allowed by UL 867, the indoor ozone concentration would be below 50 ppb in greater than 99.9% of homes; the average concentration would be about 12 ppb.

With the two-zone model, ozone levels were estimated with the bedroom door closed or open. With the bedroom door closed, ozone levels in the bedroom (zone 1) were virtually identical to the levels estimated with the one-zone model (Figure 3). With the bedroom open, ozone levels in the bedroom were lower, while levels in the rest of the house (zone 2) increased, but did not equal the levels in zone 1 (Figure 4). As the rate of mixing between zones increases, the ozone emitted by the source is essentially diluted into a larger volume. Thus, the concentration in zone 1 will decrease, while the concentration in zone 2 increases. The two-concentrations will approach one another, but will never be equal. Further, the concentrations will always be lower than the concentration in zone 1 with the door closed.

Finally, a multiple-zone model was used to simulate a scenario in which three ozone-generating air cleaners are operating simultaneously in three different bedrooms. In this scenario, the three sources and three bedrooms behave as three independent zones. Ozone levels were maintained at or below 50 ppb at source strengths up to 7 cc/h (14 mg/h) (Table 6). Thus, operating multiple UL-compliant air cleaners in different rooms would not raise indoor ozone levels above 50 ppb. However, operating multiple air cleaners in the same room may result in ozone levels above 50 ppb.

Based on our analysis, UL 867 is adequate to maintain indoor ozone levels below the recommended 50 ppb level in virtually all homes. Furthermore, the design of UL 867 may tend to overestimate ozone emissions by 2-to3-fold (see above). Therefore, the estimated ozone levels in Table 5 may also be overestimated by 2-to-3-fold.

Jakober and Phillips tested ozone-generating air cleaners in a 20 m^3 test room with an infiltration rate of 0.27 h^{-1} (Jakober and Phillips 2008) They tested air cleaners with ozone source strengths ranging from 0.5-to-2.9 mg/h (0.25-to-1.5 cc/h). The maximum ozone concentrations in the test room ranged from 1-to-14 ppb. This is consistent with the CPSC staff conclusions that limiting the ozone emission rate to 2 cc/h (4 mg/h) or less would maintain indoor ozone levels below 50 ppb.

Mass-Balance Models

Mass balance models are widely used to assess indoor air quality and are generally considered reliable (NRC 1981). Nevertheless, they are based on certain assumptions, such as steady-state conditions and well-mixed compartments. The use of any model to estimate exposure introduces sources of uncertainty that are difficult to quantify. In the present case, parameters such as the deposition velocity and surface area-to-volume ratio are highly variable. Studies in test homes or actual residences are always preferable to modeling (CPSC 1992). Limited data from a test room (Jakober and Phillips 2008) are consistent with the modeling results presented here.

The reactive decay of ozone with surfaces in the home can be modeled in either of two ways: (a) as an apparent first-order decay rate with dimensions of $time^{-1}$; or (b) as a second order reaction that depends on a reaction rate (deposition velocity) and surface area (Lee et al. 1999). The relationship between the two approaches is described by:

$$k = v\frac{A}{V} \tag{20}$$

where : k, first-order decay rate, h^{-1}; v, deposition velocity, m/h; A, surface area, m^2; and V, volume, m^3.

Although the two approaches are mathematically equivalent, the surface area-to-volume ratio (A/V) generally decreases with increasing room volume (Hodgson et al. 2004). The first order decay rate (k) also decreases as a function of the room volume. When modeling only average conditions, this should not affect the results. However, when considering the ranges of various input parameters, such as for probabilistic modeling, it is necessary to account for the dependence of decay on the surface area-to-volume ratio. Therefore, reactive decay was modeled as a second order process.

The dependence of A/V on room volume also made it necessary to match A/V data to the volume of the room being modeled. To accomplish this, the total surface area-to-volume ratio (A/V) was modeled as a function of the surface area-to-volume ratio for an unoccupied room. This was accomplished by reanalyzing the data of Hodgson et al. (2004). Shaughnessy used an essentially similar approach, in which A/V was modeled as a function of floor surface area (Shaughnessy 2006, Figure 1).

Data on ozone decay rates and surface area-to-volume ratios are somewhat limited. Decay rates were from a sample of 43 homes in Southern California (Lee et al. 1996). The rate of ozone decay is specific for different materials and may vary widely (Morrison et al. 2000; Mueller et al. 1973; Poppendieck et al. 2007; Sabersky et al. 1973; Weschler 2000; Weschler et al. 1992). Porous materials such as carpet and upholstery have greater decay rates than non-porous surfaces, such as wood floors. Thus, the ozone rates measured in homes are actually average values for many different surfaces. Furthermore, the decay rate in a given residence may vary depending on the type of floor covering, the presence of a gas stove, house type, and the type of room (Lee et al. 1996; Mueller et al. 1973). Other conditions such as temperature and humidity also influence ozone decay.

Surface area-to-volume ratios were from measurements in 33 rooms (Hodgson et al. 2004). Rooms were categorized as common areas (living room, dining room, kitchen, or hallway), bedroom/office, or bathroom. Common areas tended to have lower surface area-to-volume areas than other rooms. Bathrooms tended to have higher ratios, but they are also smaller in size. Bedrooms/offices tended to be intermediate. Overall, the values tended to fit the model described in Figure 1. Thus, all of the data were used to model the surface area-to-volume ratio.

<u>Secondary Reaction Products</u>

While ozone reacts with indoor surfaces, it may also react with other pollutants in indoor air, principally volatile organic compounds (VOC's) (for example, Sarwar and Corsi 2007; Weschler 2000; Weschler et al. 1992). This may lead to the formation of secondary reaction products, such as aldehydes and fine particles, which also have significant toxicity. Modeling the formation of secondary reaction products is beyond the scope of this analysis. However, limiting the emission of ozone from air cleaning devices will also limit the formation of secondary reaction products.

Conclusions

Based on the modeling of ozone emissions from air cleaners, we conclude that UL 867 is adequate to maintain ozone levels below 50 ppb in residences under reasonably foreseeable use conditions. Assuming the operation of one UL 867-compliant air cleaner in a bedroom with the door closed, we estimate that the steady-state ozone level will be below 50 ppb in greater than 99.9% of cases. This analysis encompasses variability in homes, including: room size, infiltration rate, total house size, reactive decay rate, and ambient ozone levels. The analysis also includes regional and seasonal variation, and the simultaneous operation of multiple air cleaners in different rooms. Limited experimental data (Jakober and Phillips 2008) are consistent with the modeling studies present here.

Furthermore, UL 867 specifies that ozone measurements be made near the source at the maximum level, rather than elsewhere in the test chamber, which is the typical practice for measuring source strengths. This procedure is intended to protect consumers who may place the air cleaner near the breathing zone, which is not recommended. However, the procedure also overestimates the ozone source strength by 2-to-3-fold. Therefore, our analysis likely overestimates the average indoor ozone levels, that is, the levels a few feet away from the source. This, in effect, provides an additional safety factor of 2-to-3-fold for consumers who position the air cleaner away from their breathing zone.

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Table 1. Ozone Conversion Factors

Concentration in Air	Source Strength
1 part-per-million (ppm) equals:	1 cubic centimeter per hour (cc/h) equals:
1 cubic centimeter (ozone) per cubic meter (air) (cc/m^3)	1.98 milligrams per hour (mg/h)
1000 parts-per-billion (ppb)	
1.98 milligrams of ozone per cubic meter of air (mg/m^3)	

Table 2. Input Parameters

Parameter	Symbol	Units	Mean	SD [a]	Median [b]	N	Distribution Type [c]	Reference
Air exchange rate, interzone	a_{12}	m^3/h	2.5	-- [d]	--	--	Fixed; Door closed	Shair 1982
			500	--	--	--	Fixed; Door open	
Air infiltration rate	a	h^{-1}	0.76	0.88	0.51	2,844	Discrete; All seasons/regions	Murray & Burmeister 1995
Concentration, ambient	C_0	cc/m^3	0.033	--	0.0325	345,506	Discrete; All seasons/regions	EPA 2006
Deposition velocity [e]	v	m/h	1.76	0.61	--	43	Lognormal	Lee et al. 1999
Room height	H	m	2.5	--	--	--	Fixed	Assumption
Ratio [e]	R	unitless	1.74	0.37	1.81	33	Discrete; All rooms	Hodgson et al. 2004
Volume, total	V_T	m^3	382	242	316	7,000	Discrete; All regions	Murray 1997
Volume, bedroom [f]	V_1	m^3	41.6	13.4	38.1	114	Weighted discrete; All homes	Persily et al. 2006
			33.8	7.1	36.2	36	$V_T < 360\ m^3$	
			48.1	13.1	49.8	51	V_T 360—540 m^3	
			51.0	15.4	48.9	27	$V_T > 540\ m^3$	

[a] Standard deviation.

[b] The median was generally used for deterministic calculations.

[c] Type of distribution for probabilistic calculations; data subset.

[d] Not applicable or not reported.

[e] With the two-zone model, the deposition velocity and ratio were sampled independently for zones 1 and 2.

[f] The volumes from all homes were used in the one-zone model. For the two-zone model, bedroom volumes were stratified by size.

Table 3. One-Zone Model—Effect of Model Inputs on Indoor Ozone Levels

a [a] h^{-1}	C_0, cc/m^3	V m^3	v m/h	R unitless	A/V [b] m^2/m^3	C [c] ppb	Comment
0.51	0.0325	38.1	1.76	1.81	3.3	10.9	Average conditions [d]
0.51	0.0325	20.0 [e]	1.76	1.81	4.0	15.4	Small bedroom [f]
0.51	0.12	38.1	1.76	1.81	3.3	18.0	High ambient ozone
2.00	0.12	38.1	1.76	1.81	3.3	37.4	High ambient ozone and infiltration rate
0.35	0	40	1.76	1.95	3.5	7.73	Shaughnessy 2006 [g]
0.35	0	15	1.76	2.10	5.0	14.2	Shaughnessy 2006 [g]
0.15	0.12	20.0	1.00	1.00	2.2	79.8	Extreme worst case

[a] a, infiltration rate; C_0, ambient ozone; v, deposition velocity; R, ratio of total surface area to envelope surface area (see text); V, volume; S, source strength..

[b] A/V is calculated from R (see text).

[c] Calculated with equation (1).

[d] Median values (see Table 2).

[e] Shaded cells indicate changes from average conditions.

[f] 20 m^3 is approximately equal to an 8x10 foot room.

[g] These include the range of input values modeled by Shaughnessy (2006).

Table 4. Estimated maximum source strength (cc/h) for ozone-generating air cleaners. [a]

Model	Mean	SD	Percentiles				
			5	10	50	90	95
One-zone	11.9	5.71	4.9	5.8	10.7	19.3	22.8
Two-zone, door closed	13.2	6.35	5.7	6.6	11.9	21.5	25.4

[a] The maximum source strength is the source strength associated with 50 ppb indoor ozone. 1 cc/h equals 1.98 mg/h.

Table 5. Estimated indoor ozone levels (ppb) from use of ozone-generating air cleaners. [a]

Model	S	Zone	Mean	SD	Percentiles			<50 ppb [b]
	cc/h				5th	50th	95th	%
One-zone	2.0	1	14.0	6.7	5.9	12.5	26.8	>99.9
	5.0	1	28.0	12.0	12.9	25.8	50.5	94.7
	10.0	1	51.3	22.3	23.6	46.9	93.7	55.8
Two-zone, door closed	2.0	1	14.0	6.7	5.9	12.6	27.2	>99.9
		2	6.3	6.8	0.64	4.0	20.4	>99.9
	5.0	1	27.8	11.6	12.8	25.8	49.6	99.3
		2	6.4	6.8	0.70	4.0	20.4	>99.9
	10.0	1	50.9	21.9	23.3	46.9	92.6	56.5.8
		2	6.4	6.8	0.77	4.1	20.6	>99.9
Two-zone, door open	10.0	1	23.5	7.1	14.3	22.2	36.8	99.5
		2	12.5	7.5	3.7	10.8	27.0	99.9

[a] Estimated with mass balance models using probabilistic methods (see text).

[b] Percentage of cases (total 25,000 iterations) with less than 50 ppb ozone.

Table 6. Estimated indoor ozone levels (ppb) in a residence with three ozone-generating air cleaners.[a]

Source Strength (cc/h)	Ozone Concentration (ppb)				
	Zone 1 [b]	Zone 2 [b]	Zone 3 [b]	Zone 4	Zone 5
	Bedroom 1 [c]	Bedroom 2	Bedroom 3	Hallway	Other
	50 m^3	30 m^3	20 m^3	10 m^3	206 m^3
2.0	10.0	12.9	16.0	3.3	3.7
5.0	20.6	28.2	36.4	3.6	3.8
7.0	27.6	38.5	50.1 [d]	3.8	3.9
10.0	38.1	53.8	70.5	4.0	4.0

[a] Estimated with the multiple-zone mass balance model (see text).

[b] Identical sources located in these zones; door are assumed to be closed.

[c] Interzone air exchange rates between the bedrooms and the hallway were assumed to be 2.5 m^3/h (doors closed) (see Table 2). The interzone air exchange rate between the hallway (zone 4) and zone 5 was assumed to be 500 m^3/h (door open). All other parameters are the median values described in Table 2.

[d] Shaded cells are concentrations ≥ 50 ppb.

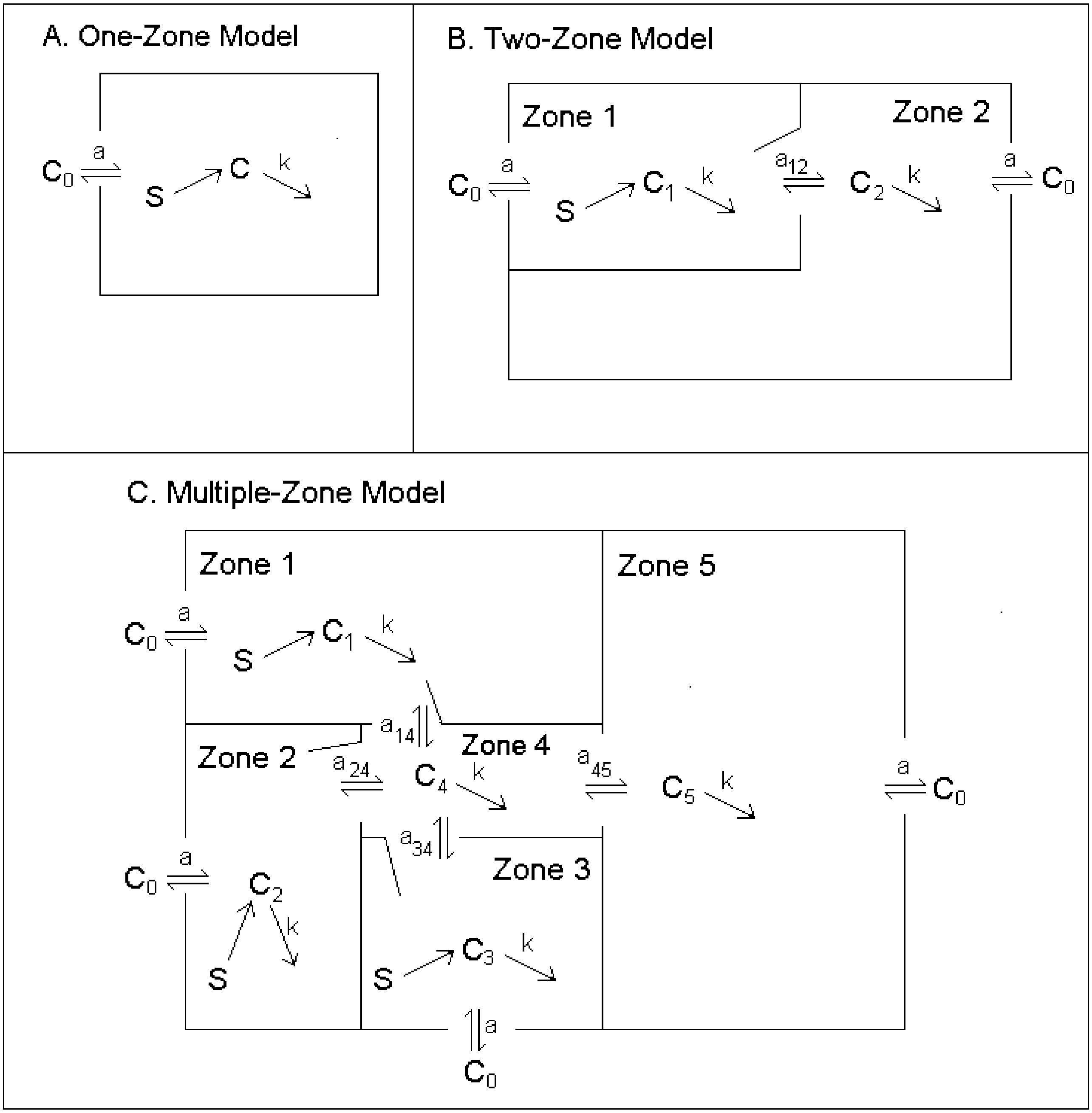

Figure 1. Schematics of mass-balance models.

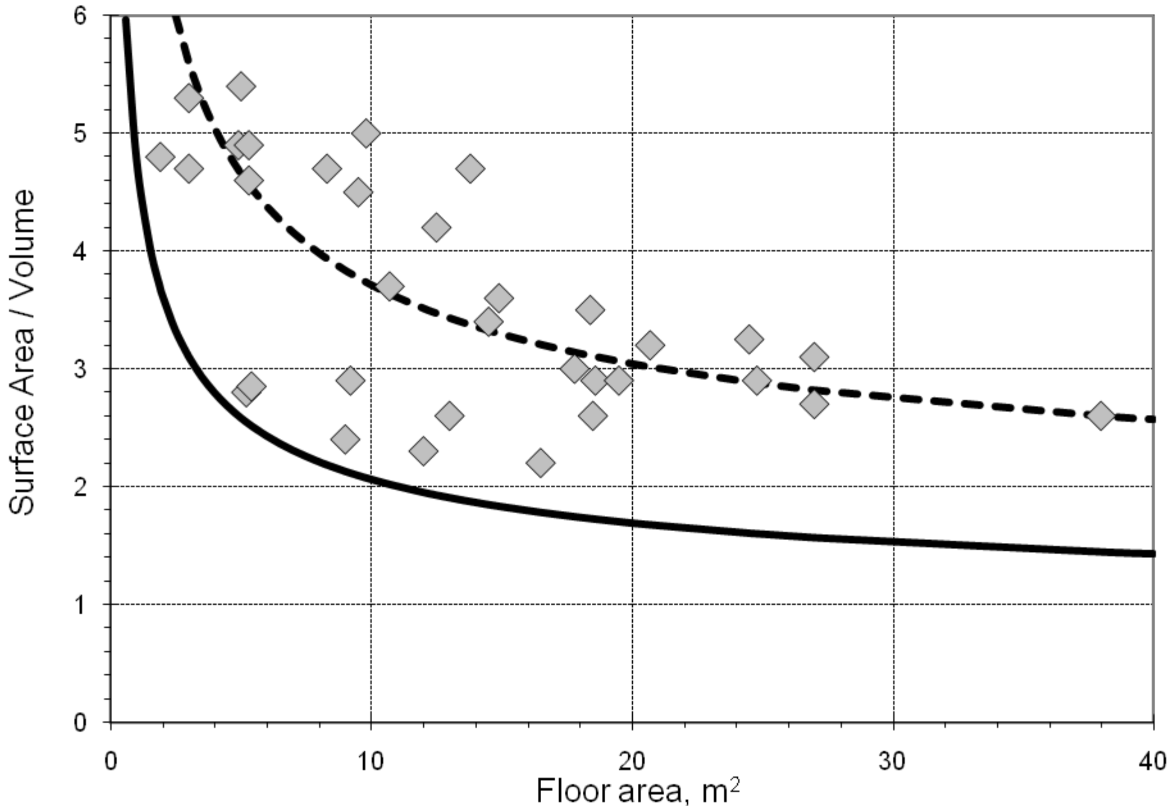

Figure 2. Surface: volume ratio (m^2/m^3) in residences (adapted from Hodgson et al. 2004). Symbols (◊) are the measured total surface area/volume for all room types (Hodgson et al. 2004); the solid line (——) is the ratio of the room envelope area/volume (theoretical); the broken line (- - - -) is the best fit (see text).

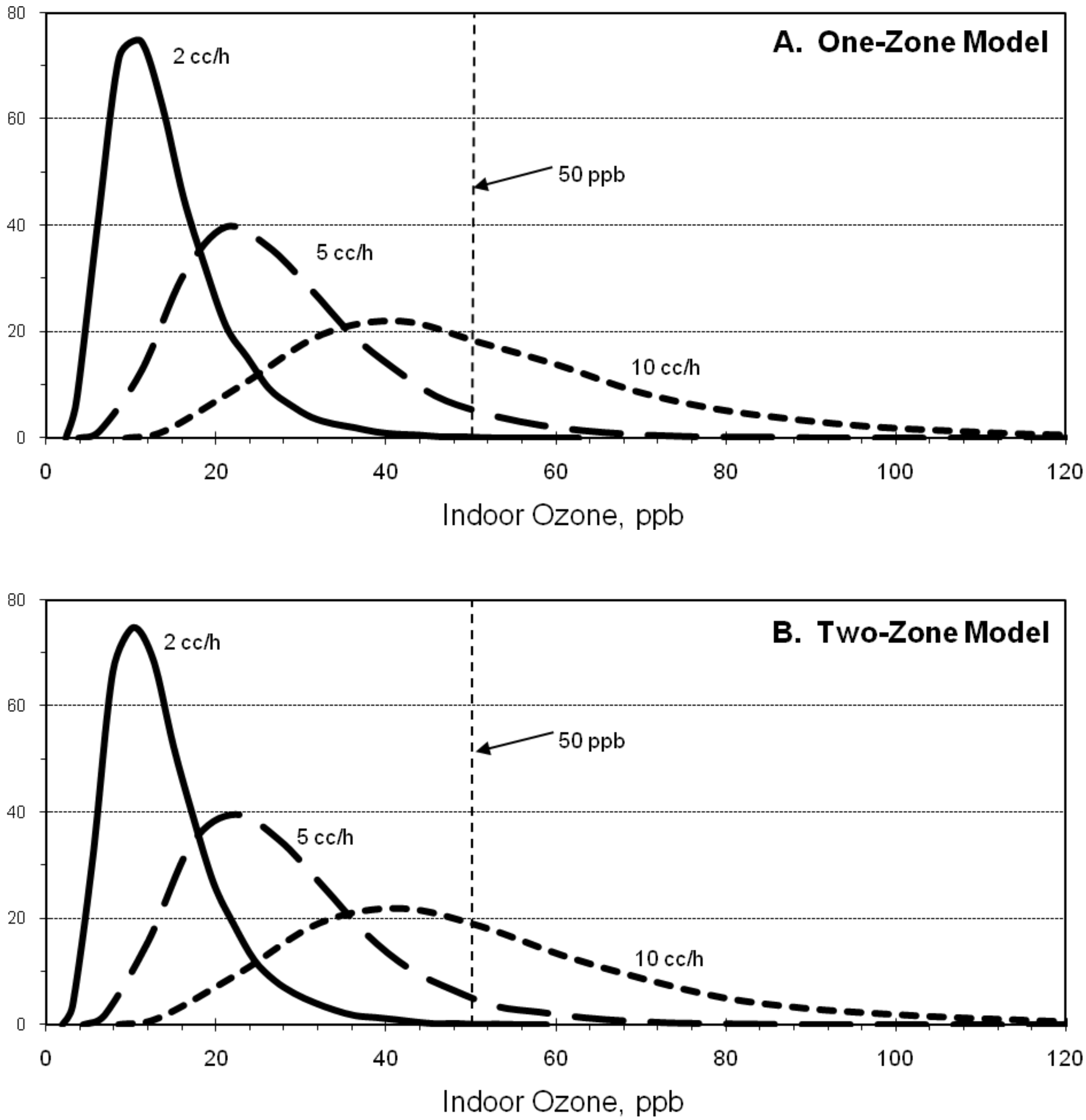

Figure 3. Modeled distributions of indoor ozone levels in homes with source strength 2 cc/h (——), 5 cc/h (- - -), or 10 cc/h (······). A. One-zone model. B. Two-zone model (Zone 1 shown).
What's the legend for the vertical axis?

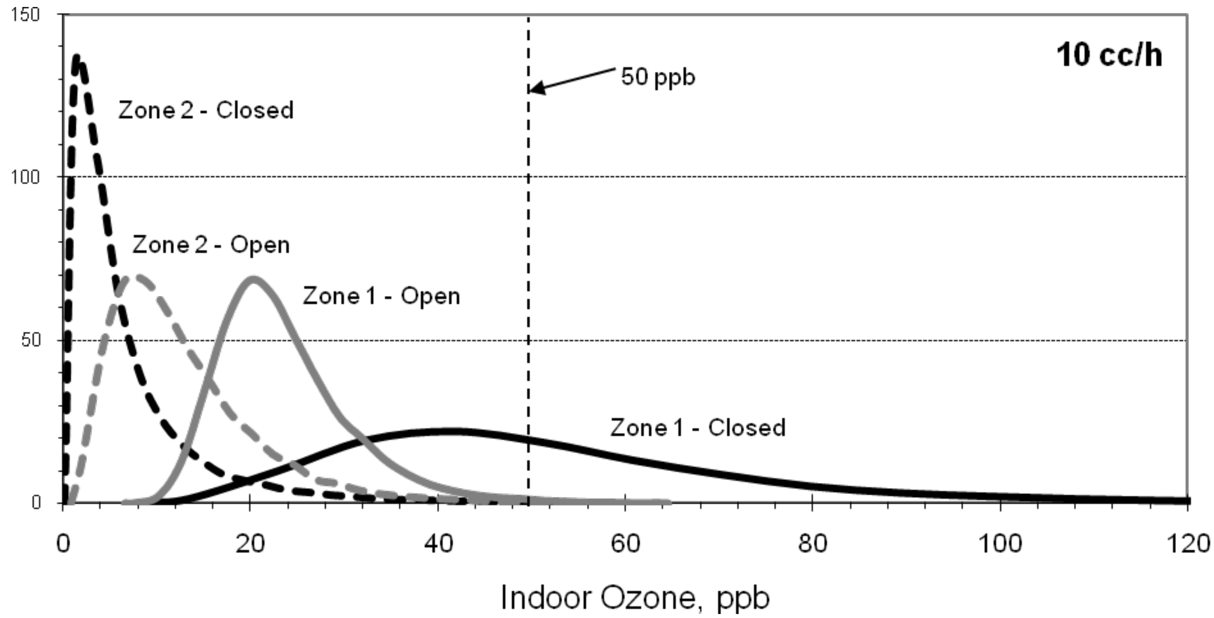

Figure 4. Effect of opening the interior door on modeled distributions of indoor ozone levels. Two-zone model; source strength 10 cc/h. Door closed: zone 1 (—), zone 2 (----). Door open: zone 1 (—), zone 2 (----).

What's the legend for the vertical axis?

APPENDIX A. Derivation of Equations

One-Zone Model

Let C be the ozone concentration (cc/m^3, ppm) in a single compartment, with a point source S (cc/h), and an ambient concentration C_0 (cc/m^3). Ozone decays by reaction with interior surfaces with an apparent first-order decay rate k (h^{-1}). Infiltration of ambient ozone depends on the air infiltration rate a (h^{-1}).

The rate of change in the concentration C is given by:

$$\frac{dC}{dt} = \frac{S}{V} + a \cdot C_0 - a \cdot C - k \cdot C \tag{21}$$

where: C, concentration, cc/m^3; t, time, h; S, source strength, cc/h; V, volume, m^3; a, air infiltration rate, h^{-1}; k, apparent first-order decay rate, h^{-1}.

Combining terms:

$$\frac{dC}{dt} = \frac{S}{V} + a \cdot C_0 - \left(a + k\right) \cdot C \tag{22}$$

At steady-state:

$$\frac{dC}{dt} = 0 = \frac{S}{V} + a \cdot C_0 - \left(a + k\right) \cdot C \tag{23}$$

Rearranging:

$$\left(a + k\right) \cdot C = \frac{S}{V} + a \cdot C_0 \tag{24}$$

Solving for C:

$$C = \frac{\frac{S}{V} + a \cdot C_0}{a + k} \tag{25}$$

Deposition Velocity

Ozone decay occurs by reaction with surfaces in the compartment, such as home furnishings or the test chamber walls. The decay rate (flux) depends on the concentration and deposition velocity (Lee et al. 1999):

$$F = v \cdot C \tag{26}$$

where: F, flux, cc/m^2-h; v, deposition velocity, m/h; C, concentration, cc/m^3.

The apparent first-order decay rate is given by:

$$k = v\frac{A}{V} \tag{27}$$

where : k, first-order decay rate, h^{-1}; v, deposition velocity, m/h; A, surface area, m^2; and V, volume, m^3.

Substituting equation (20) into equation (25) gives:

$$C = \frac{\frac{S}{V} + a \cdot C_0}{a + v\frac{A}{V}} \tag{28}$$

Solving for S:

$$S = V\left[C\left(a + v\frac{A}{V}\right) - a \cdot C_0\right] \tag{29}$$

UL Standard 867

UL 867 requires ozone generators to be tested in a chamber with a net apparent decay rate N_{App} of 1.33 h^{-1} (UL 2000), which is given by:

$$N_{App} = a + v\frac{A}{V} \tag{30}$$

Substituting equation (30) into equation (29) gives:

$$S = V\left[C \cdot N_{App} - a \cdot C_0\right] \tag{31}$$

If C_0 is zero:

$$S = V \cdot C \cdot N_{App} \tag{32}$$

Two-Zone Model

Let C_1 and C_2 be the ozone concentration (cc/m^3) in the zones 1 and 2, respectively, with a point source S (cc/h) in zone 1, and an ambient concentration C_0 (cc/m^3). Ozone decays by reaction with interior surfaces with an apparent first-order decay rate k (h^{-1}). Infiltration of ambient ozone depends on the air infiltration rate a (h^{-1}).

Then the rate of change in the indoor concentration C_1 is given by:

$$\frac{dC_1}{dt} = \frac{S}{V_1} + a \cdot C_0 + \frac{a_{12} \cdot C_2}{V_1} - \frac{a_{12} \cdot C_1}{V_1} - a \cdot C_1 - k \cdot C_1 \tag{33}$$

where: C_1, concentration, cc/m^3; C_2, concentration, cc/m^3; t, time, h; S, source strength, cc/h; V, volume, m^3; a, air infiltration rate, h^{-1}; a_{12}, inter-zone air exchange rate, m^3/h; k, apparent first-order decay rate, h^{-1}.

Combining terms:

$$\frac{dC_1}{dt} = \frac{S}{V_1} + a \cdot C_0 + \frac{a_{12} \cdot (C_2 - C_1)}{V_1} - (a + k) \cdot C_1 \tag{34}$$

Similarly, the rate of change in the indoor concentration C_2 is given by:

$$\frac{dC_2}{dt} = a \cdot C_0 + \frac{a_{12} \cdot C_1}{V_2} - \frac{a_{12} \cdot C_2}{V_2} - a \cdot C_2 - k \cdot C_2 \tag{35}$$

And:

$$\frac{dC_2}{dt} = a \cdot C_0 + \frac{a_{12} \cdot (C_1 - C_2)}{V_2} - (a + k) \cdot C_2 \tag{36}$$

Multiplying equations (34) and (36) by dt gives:

$$dC_1 = \left[\frac{S}{V_1} + a \cdot C_0 + \frac{a_{12} \cdot (C_2 - C_1)}{V_1} - (a + k) \cdot C_1 \right] dt \tag{37}$$

$$dC_2 = \left[a \cdot C_0 + \frac{a_{12} \cdot (C_1 - C_2)}{V_2} - (a + k) \cdot C_2 \right] dt \tag{38}$$

At steady-state, equation (33) becomes:

$$\frac{dC_1}{dt} = 0 = \frac{S}{V_1} + a \cdot C_0 + \frac{a_{12} \cdot C_2}{V_1} - \frac{a_{12} \cdot C_1}{V_1} - a \cdot C_1 - k \cdot C_1 \tag{39}$$

Rearranging:

$$\frac{a_{12} \cdot C_1}{V_1} + a \cdot C_1 + k \cdot C_1 = \frac{S}{V_1} + a \cdot C_0 + \frac{a_{12} \cdot C_2}{V_1} \tag{40}$$

Factoring: $$\left(\frac{a_{12}}{V_1}+a+k\right)\cdot C_1=\frac{S}{V_1}+a\cdot C_0+\frac{a_{12}\cdot C_2}{V_1} \tag{41}$$

Solving for C_1: $$C_1=\left(\frac{S}{V_1}+a\cdot C_0+\frac{a_{12}\cdot C_2}{V_1}\right)\bigg/\left(\frac{a_{12}}{V_1}+a+k\right) \tag{42}$$

Substituting equation (20) for k in equation (42):

$$C_1=\left(\frac{S}{V_1}+a\cdot C_0+\frac{a_{12}\cdot C_2}{V_1}\right)\bigg/\left(\frac{a_{12}}{V_1}+a+v\frac{A_1}{V_1}\right) \tag{43}$$

Multiplying by V_1/V_1:

$$\boxed{C_1=\frac{S+a\cdot C_0\cdot V_1+a_{12}\cdot C_2}{a_{12}+a\cdot V_1+v\cdot A_1}} \tag{44}$$

Similarly, at steady-state, equation (34) becomes:

$$\frac{dC_2}{dt}=0=a\cdot C_0+\frac{a_{12}\cdot C_1}{V_2}-\frac{a_{12}\cdot C_2}{V_2}-a\cdot C_2-k\cdot C_2 \tag{45}$$

Rearranging: $$\frac{a_{12}\cdot C_2}{V_2}+a\cdot C_2+k\cdot C_2=a\cdot C_0+\frac{a_{12}\cdot C_1}{V_2} \tag{46}$$

Factoring: $$\left(\frac{a_{12}}{V_2}+a+k\right)\cdot C_2=a\cdot C_0+\frac{a_{12}\cdot C_1}{V_2} \tag{47}$$

Solving for C_2: $$C_2=\left(a\cdot C_0+\frac{a_{12}\cdot C_1}{V_2}\right)\bigg/\left(\frac{a_{12}}{V_2}+a+k\right) \tag{48}$$

Substituting for k and multiplying by V_2/V_2:

$$\boxed{C_2=\frac{a\cdot C_0\cdot V_2+a_{12}\cdot C_1}{a_{12}+a\cdot V_2+v\cdot A_2}} \tag{49}$$

Solve for S

Multiply equation (8) by the denominator:

$$C_1\left(a_{12}+a\cdot V_1+v\cdot A_1\right)=S+a\cdot C_0\cdot V_1+a_{12}\cdot C_2 \tag{50}$$

Expand:
$$a_{12}\cdot C_1+a\cdot C_1\cdot V_1+v\cdot A_1=S+a\cdot C_0\cdot V_1+a_{12}\cdot C_2 \tag{51}$$

Rearranging:
$$a_{12}\cdot C_1+a\cdot C_1\cdot V_1+v\cdot A_1-a\cdot C_0\cdot V_1-a_{12}\cdot C_2=S \tag{52}$$

Simplify:
$$\boxed{S=a_{12}\cdot\left(C_1-C_2\right)+a\cdot V_1\left(C_1-C_0\right)+v\cdot A_1} \tag{53}$$

Alternative Solution for C_1

Equations (8) and (9) are simultaneous equations in two unknowns. One method of solving simultaneous equations is by substitution. Substituting equation (8) into equation (9):

$$C_1=\frac{S+a\cdot C_0\cdot V_1+a_{12}\cdot\left[\dfrac{a\cdot C_0\cdot V_2+a_{12}\cdot C_1}{a_{12}+a\cdot V_2+v\cdot A_2}\right]}{a_{12}+a\cdot V_1+v\cdot A_1} \tag{54}$$

For convenience:

$$\begin{aligned}&\text{Let } N_1=a_{12}+a\cdot V_1+v\cdot A_1\\&\text{and } N_2=a_{12}+a\cdot V_2+v\cdot A_2\end{aligned} \tag{55}$$

Substituting N_1 and N_2 into equation(54):

$$C_1=\frac{S+a\cdot C_0\cdot V_1+a_{12}\left[\dfrac{a\cdot C_0\cdot V_2+a_{12}\cdot C_1}{N_2}\right]}{N_1} \tag{56}$$

Multiply:
$$C_1=\left[\frac{1/N_1}{1/N_1}\right]\cdot\frac{S+a\cdot C_0\cdot V_1+a_{12}\left[\dfrac{a\cdot C_0\cdot V_2+a_{12}\cdot C_1}{N_2}\right]}{N_1} \tag{57}$$

Then:
$$C_1=\frac{S+a\cdot C_0\cdot V_1}{N_1}+a_{12}\left[\frac{a\cdot C_0\cdot V_2+a_{12}\cdot C_1}{N_1\cdot N_2}\right] \tag{58}$$

Expand: $$C_1 = \frac{S + a \cdot C_0 \cdot V_1}{N_1} + \frac{a \cdot a_{12} \cdot C_0 \cdot V_2}{N_1 \cdot N_2} + \frac{(a_{12})^2 \cdot C_1}{N_1 \cdot N_2} \tag{59}$$

Rearranging: $$C_1 - \frac{(a_{12})^2 \cdot C_1}{N_1 \cdot N_2} = \frac{S + a \cdot C_0 \cdot V_1}{N_1} + \frac{a \cdot a_{12} \cdot C_0 \cdot V_2}{N_1 \cdot N_2} \tag{60}$$

Factoring: $$C_1 \left[1 - \frac{(a_{12})^2}{N_1 \cdot N_2} \right] = \frac{S + a \cdot C_0 \cdot V_1}{N_1} + \frac{a \cdot a_{12} \cdot C_0 \cdot V_2}{N_1 \cdot N_2} \tag{61}$$

Solving for C_1: $$C_1 = \frac{\dfrac{S + a \cdot C_0 \cdot V_1}{N_1} + \dfrac{a \cdot a_{12} \cdot C_0 \cdot V_2}{N_1 \cdot N_2}}{1 - \dfrac{(a_{12})^2}{N_1 \cdot N_2}} \tag{62}$$

Finally, substituting for N_1 and N_2:

$$\boxed{C_1 = \frac{\dfrac{S + a \cdot C_0 \cdot V_1}{a_{12} + a \cdot V_1 + v \cdot A_1} + \dfrac{a \cdot a_{12} \cdot C_0 \cdot V_2}{[a_{12} + a \cdot V_1 + v \cdot A_1][a_{12} + a \cdot V_2 + v \cdot A_2]}}{1 - \dfrac{(a_{12})^2}{[a_{12} + a \cdot V_1 + v \cdot A_1][a_{12} + a \cdot V_2 + v \cdot A_2]}}} \tag{63}$$

Surface-to-Volume Ratio

The surface-to-volume ratio (A/V) is the ratio of the total surface area of a room—including all exposed walls, ceiling, floors, and furnishings—to the room volume. A/V is needed to calculate the decay rate, k, as in equation (20). The surface area of a room's envelope, that is, the area of the floor, ceiling, and walls only, <u>not</u> including the furnishings, is given by:

$$E = 2F + 2H(L + W) \tag{64}$$

> where: E, envelope surface area, m^2; F, floor surface area; H, room height, m; L, room length, m; and W, room width, m.

If the length and width are equal: $$E = 2F + 4H\sqrt{F} \tag{65}$$

The floor area, F, depends on the room volume, V:

$$F = V / H \tag{66}$$

Substituting equation (66) into equation (65):

$$E = 2\frac{V}{H} + 4H\sqrt{\frac{V}{H}} \tag{67}$$

The "ratio," R, is defined as the ratio of A to E. Thus:

$$R \equiv \frac{A}{E} \tag{68}$$

And:

$$A = R \cdot E \tag{69}$$

Substituting equation (67) into equation (3):

$$A = R \cdot \left[2\frac{V}{H} + 4H\sqrt{\frac{V}{H}} \right] \tag{70}$$

And

$$A/V = R \cdot \left[\frac{2\frac{V}{H} + 4H\sqrt{\frac{V}{H}}}{V} \right] \tag{71}$$

Thus, the total surface area A is a function of R, V, and H. The room height H is constant. The ratio R and volume V are variables that may be estimated from empirical data. For simplicity, equation (70) assumes that the room length and width are equal. Changing to aspect ratio from 1:1 to 3:1 would increase A/V by 5-to10%.

Multiple-Zone Model

By analogy to the two-zone model, as described in equation (33), the concentration in any zone of the multiple-zone model is given by:

$$\frac{dC_i}{dt} = \frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot C_j}{V_i} - \frac{\sum_j a_{ij} \cdot C_i}{V_i} - a_i \cdot C_i + k_i \cdot C_i \tag{72}$$

where: $a_{ii} \equiv 0$ and where: $a_{ij} \equiv a_{ji}$

and where: C_i, concentration in the i-th zone, cc/m^3; C_j, concentrations in all other zones, cc/m^3; t, time, h; S_i, source strength, cc/h; V_i, volume, m^3; a_i, air infiltration rate, h^{-1}; a_{ij}, inter-zone air exchange rate between the i-th and j-th zones, m^3/h; k_i, apparent first-order decay rate, h^{-1}.

Substituting equation (20) for *k* in equation (72) gives:

$$\frac{dC_i}{dt} = \frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot C_j}{V_i} - \frac{\sum_j a_{ij} \cdot C_i}{V_i} - a_i \cdot C_i + v_i \cdot \left(\frac{A_i}{V_i} \right) \cdot C_i \qquad (73)$$

Combining terms:

$$\frac{dC_i}{dt} = \frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot \left(C_j - C_i \right)}{V_i} - \left(a_i + v_i \cdot \frac{A_i}{V_i} \right) \cdot C_i \qquad (74)$$

Solving for dC_i:

$$\boxed{dC_i = \left[\frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot \left(C_j - C_i \right)}{V_i} - \left(a_i + v \cdot \frac{A_i}{V_i} \right) \cdot C_i \right] \cdot dt \qquad (75)}$$

Equation (75) represents a set of *k* time-dependent equations that may be solved by Euler's method, where *k* is the number of zones.

At steady-state, equation (73) may be set to zero:

$$0 = \frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot C_j}{V_i} - \frac{\sum_j a_{ij} \cdot C_i}{V_i} - a_i \cdot C_i + v_i \cdot \left(\frac{A_i}{V_i} \right) \cdot C_i \qquad (76)$$

Combining the last two terms:

$$0 = \frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot C_j}{V_i} - \frac{\sum_j a_{ij} \cdot C_i}{V_i} - \left(a_i + v_i \cdot \frac{A_i}{V_i} \right) \cdot C_i \qquad (77)$$

Moving C_i outside the summation sign (commutative property):

$$0 = \frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot C_j}{V_i} - \frac{C_i \cdot \sum_j a_{ij}}{V_i} - \left(a_i + v_i \cdot \frac{A_i}{V_i} \right) \cdot C_i \qquad (78)$$

Rearranging:

$$\left(a_i + v_i \cdot \frac{A_i}{V_i}\right) \cdot C_i + \frac{C_i \cdot \sum_j a_{ij}}{V_i} = \frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot C_j}{V_i} \tag{79}$$

Factoring:

$$C_i \cdot \left(a_i + v_i \frac{A_i}{V_i} + \frac{\sum_j a_{ij}}{V_i}\right) = \frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot C_j}{V_i} \tag{80}$$

Solving for C_i:

$$C_i = \left(\frac{S_i}{V_i} + a_i \cdot C_0 + \frac{\sum_j a_{ij} \cdot C_j}{V_i}\right) \Bigg/ \left(a_i + v_i \frac{A_i}{V_i} + \frac{\sum_j a_{ij}}{V_i}\right) \tag{81}$$

Multiplying by V_i/V_i:

$$\boxed{C_i = \frac{S_i + a_i \cdot C_0 \cdot V_i + \sum_j a_{ij} \cdot C_j}{a_i \cdot V_i + v_i \cdot A_i + \sum_j a_{ij}}} \tag{82}$$

Equation (82) represents a set of *k* simultaneous equations giving the steady-state concentrations in each of *k* zones.

For convenience:

$$\begin{aligned} &\text{Let } X_i = \sum_j a_{ij} \cdot C_j \\ &\text{and } Y_i = \sum_j a_{ij} \end{aligned} \tag{83}$$

Expanding:

$$\begin{aligned} &X_i = a_{i1}C_1 + a_{i2}C_2 + a_{i3}C_3 + \ldots \\ &\text{and} \\ &Y_i = a_{i1} + a_{i2} + a_{i3} + \ldots \end{aligned} \tag{84}$$

<u>Application to Ozone Generators</u>

The multiple-zone model will be used to model a scenario in which three ozone sources are operating simultaneously in three bedrooms; no other indoor ozone sources are present. We will assume that the bedrooms open onto a common hallway that opens onto the rest of the house, e.g., living room, dining room, and kitchen. Thus, there are five zones: 3 bedrooms, a hallway, and the rest of the house. The hallway does not exchange air directly with the outside. For simplicity, the decay rates and air infiltration rates of all rooms except the hallway are assumed to be equal, and the ozone source strengths are all equal. Based on this scenario, equation (84) becomes:

Bedrooms (zones 1-3):

$$X_1 = a_{14} \cdot C_4 \text{ and } Y_1 = a_{14}$$
$$X_2 = a_{24} \cdot C_4 \text{ and } Y_2 = a_{24} \qquad (85)$$
$$X_3 = a_{34} \cdot C_4 \text{ and } Y_3 = a_{34}$$

Hallway (zone 4):

$$X_4 = a_{14} \cdot C_1 + a_{24} \cdot C_2 + a_{34} \cdot C_3 + a_{45} \cdot C_5$$
$$\text{and} \qquad (86)$$
$$Y_4 = a_{14} + a_{24} + a_{34} + a_{45}$$

Other rooms (zone 5):

$$X_5 = a_{45} \cdot C_4 \text{ and } Y_5 = a_{45} \qquad (87)$$

Substituting equations (85), (86), and (87) into equation (82), and applying the assumptions that sources in zones 1-3 are equal, all decay rates are equal, and all air infiltration rates are equal (except zone 4, which has a zero infiltration rate), results in:

$$C_1 = \frac{S + a \cdot C_0 \cdot V_1 + a_{14} \cdot C_4}{a \cdot V_1 + v \cdot A_1 + a_{14}} \qquad (88)$$

$$C_2 = \frac{S + a \cdot C_0 \cdot V_2 + a_{24} \cdot C_4}{a \cdot V_2 + v \cdot A_2 + a_{24}} \qquad (89)$$

$$C_3 = \frac{S + a \cdot C_0 \cdot V_3 + a_{34} \cdot C_4}{a \cdot V_3 + v \cdot A_3 + a_{34}} \qquad (90)$$

$$C_4 = \frac{a_{14} \cdot C_1 + a_{24} \cdot C_2 + a_{34} \cdot C_3 + a_{45} \cdot C_5}{v \cdot A_4 + a_{14} + a_{24} + a_{34} + a_{45}} \qquad (91)$$

$$C_5 = \frac{a \cdot C_0 \cdot V_5 + a_{45} \cdot C_4}{a \cdot V_5 + v \cdot A_5 + a_{45}} \qquad (92)$$

APPENDIX B. Input Parameters

Table B-1. Total House Volume, m^3 (Murray 1997) [a]

N	Mean	SD	Percentiles 1	5	10	20	25	30	40	50	60	70	75	80	90	95	99
7000	382	242	87	126	154	193	212	226	269	316	379	450	493	541	691	840	1226

[a] Based on heated volume, U.S.Department of Energy Residential Energy Consumption Survey.

Table B-2. Air Infiltration Rate, h^{-1} (Murray and Burmeister 1995) [a]

N	Mean	SD	Percentiles 1	5	10	20	25	30	40	50	60	70	75	80	90	95	99
2844	0.76	0.88	0.08	0.15	0.21	0.28	0.32	0.35	0.41	0.51	0.61	0.77	0.87	1.00	1.48	2.19	4.76

[a] Perfluorocarbon tracer data (Koontz and Rector 1993).

Table B-3. Ambient Ozone Level (ppb) (EPA 2006, Volume II, Table AX3-2). [a]

N	Mean	Percentiles 1	5	10	25	30	50	70	75	90	95	99
345,506	0.0335	0.01	0.015	0.018	0.0245	0.0265	0.0325	0.039	0.041	0.05	0.056	0.068

[a] 24-Hour average, pooled concentrations for all monitoring sites, May through September, 2000 through 2004. Data for consolidated metropolitan areas (CSA's) and non-CSA's were averaged.

Table B-4. Ratio of the Total Surface Area to the Envelope Surface Area [a]

N	Mean	SD	Median	Observations											
33	1.74	0.37	1.81	1.30	1.51	1.70	1.88	2.09	1.10	1.93	1.81	1.13	2.15	1.13	1.37
				2.15	2.41	1.83	1.18	2.17	1.36	2.50	1.84	1.96	1.23	1.72	2.02
				1.50	1.68	1.70	1.91	2.02	1.81	1.97	1.72	1.79			

[a] Derived from data in Hodgson et al. 2004.

Table B5. Bedroom Volumes, m^3 [a]

House volume	<360 m^3		360—540 m^3		>540 m^3		All	
N	36		51		27		114	
Mean [b]	33.8		48.1		51.0		41.6	
SD	7.1		13.1		15.4		13.4	
Median	36.2		49.8		48.9		38.1	
Data	Volume	Weight [c]	Volume	Weight	Volume	Weight	Volume	Weight
	44	0.0456	50	0.0044	62	0.0250	44	0.0222
	50	0.0456	24	0.0044	38	0.0250	50	0.0222
	36	0.0452	31	0.0044	53	0.0250	36	0.0220
	38	0.0452	84	0.0044	53	0.0250	38	0.0220
	23	0.0452	39	0.0043	56	0.0108	23	0.0220
	38	0.0162	26	0.0043	38	0.0108	38	0.0079
	45	0.0162	31	0.0043	53	0.0108	45	0.0079
	36	0.0061	65	0.1143	82	0.0314	36	0.0030
	38	0.0061	51	0.1143	49	0.0314	38	0.0030
	23	0.0061	44	0.1143	33	0.0314	23	0.0030
	32	0.0033	58	0.0050	49	0.0314	32	0.0016
	32	0.0033	51	0.0050	82	0.0264	32	0.0016
	25	0.0033	44	0.0050	49	0.0264	25	0.0016
	38	0.0121	65	0.0144	33	0.0264	38	0.0059
	36	0.0121	51	0.0144	49	0.0264	36	0.0059
	27	0.0121	32	0.0144	82	0.0437	27	0.0059
	38	0.0864	47	0.0094	49	0.0437	38	0.0421
	36	0.0864	49	0.0094	60	0.0437	36	0.0421
	27	0.0864	48	0.0094	49	0.0437	27	0.0421
	27	0.0618	32	0.0204	41	0.0723	27	0.0301
	27	0.0618	63	0.0204	49	0.0723	27	0.0301
	32	0.0618	48	0.0204	75	0.0723	32	0.0301
	49	0.0057	17	0.0204	29	0.0723	49	0.0028
	48	0.0057	56	0.0082	57	0.0431	48	0.0028
	33	0.0036	30	0.0082	49	0.0431	33	0.0018
	22	0.0036	64	0.0082	41	0.0431	22	0.0018
	32	0.0036	56	0.0076	30	0.0431	32	0.0018
	33	0.0034	30	0.0076			33	0.0016
	22	0.0034	34	0.0076			22	0.0016
	32	0.0034	34	0.0076			32	0.0016
	32	0.0626	38	0.0371			32	0.0305
	25	0.0626	53	0.0371			25	0.0305
	39	0.0626	42	0.0371			39	0.0305
	27	0.0039	63	0.0371			27	0.0019
	41	0.0039	46	0.0038			41	0.0019
	32	0.0039	71	0.0038			32	0.0019

House volume Data	<360 m^3		360—540 m^3		>540 m^3		All	
	Volume	Weight	Volume	Weight	Volume	Weight	Volume	Weight
			63	0.0038			50	0.0016
			59	0.0179			24	0.0016
			34	0.0179			31	0.0016
			64	0.0179			84	0.0016
			59	0.0204			39	0.0016
			34	0.0204			26	0.0016
			22	0.0204			31	0.0016
			59	0.0133			65	0.0417
			34	0.0133			51	0.0417
			64	0.0133			44	0.0417
			34	0.0133			58	0.0018
			56	0.0188			51	0.0018
			34	0.0188			44	0.0018
			34	0.0188			65	0.0053
			34	0.0188			51	0.0053
							32	0.0053
							47	0.0034
							49	0.0034
							48	0.0034
							32	0.0075
							63	0.0075
							48	0.0075
							17	0.0075
							56	0.0030
							30	0.0030
							64	0.0030
							56	0.0028
							30	0.0028
							34	0.0028
							34	0.0028
							38	0.0135
							53	0.0135
							42	0.0135
							63	0.0135
							46	0.0014
							71	0.0014
							63	0.0014
							59	0.0065
							34	0.0065
							64	0.0065
							59	0.0074
							34	0.0074

House volume	<360 m^3		360—540 m^3		>540 m^3		All	
Data	Volume	Weight	Volume	Weight	Data	Volume	Weight	Volume
							22	0.0074
							59	0.0049
							34	0.0049
							64	0.0049
							34	0.0049
							56	0.0068
							34	0.0068
							34	0.0068
							34	0.0068
							62	0.0037
							38	0.0037
							53	0.0037
							53	0.0037
							56	0.0016
							38	0.0016
							53	0.0016
							82	0.0046
							49	0.0046
							33	0.0046
							49	0.0046
							82	0.0039
							49	0.0039
							33	0.0039
							49	0.0039
							82	0.0065
							49	0.0065
							60	0.0065
							49	0.0065
							41	0.0107
							49	0.0107
							75	0.0107
							29	0.0107
							57	0.0064
							49	0.0064
							41	0.0064
							30	0.0064

[a] Derived from floor plans for detached homes (Persily et al. (2006).
[b] Summary statistics are from bootstrap analysis of the weighted data.
[c] The statistical weights in Persily et al. were scaled such that the weights in each category add to 1.0.